BIOREACTOR LANDFILL CELL FEASIBILITY STUDY– REFERENCE TO CITY OF DENTON SUBTITLE-D PERMIT #1590A LANDFILL

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The City of Denton Landfill, Permit #1590A, utilizes "Dry-Tomb" techniques for disposal and promotion of municipal solid waste stabilization, as described by the Resource Conservation and Recovery Act (RCRA) prohibition in 40 CFR. Bioreactor research suggests re-circulating leachate increases biodegradation rates and reduces long-term monitoring from fifty years to less than ten years.

Current procedures that are followed at Denton's landfill, literature review and the use of the Hydrologic Evaluation of Landfill Performance (HELP) model, suggest that a bioreactor landfill cell is worthy of further research. Re-circulating leachate and augmenting it with additional liquid will increase biodegradation and the need to design and build a landfill gas collection system to capture methane for energy recovery uses.

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TABLE OF CONTENTS

APPENDIX

LIST OF TABLES

LIST OF ILLUSTRATIONS

LIST OF EQUATIONS

CHAPTER 1

INTRODUCTION

Statement of the Problem

The City of Denton's municipal solid waste Subtitle-D landfill does not utilize any leachate re-circulation or other bioreactor-type technology. This document considers the application of this emerging technology to the city's current methodologies.

Evolution from Dump to Landfill

The elimination of garbage burning in backyards and factories resulted in increased amounts of garbage to be collected for disposal. The national movement in solid waste management during the 1940-1970s, was based primarily on public health concerns. Figure 1 and 2 show collection methods utilized by the City of Memphis, TN (Solid Waste Management, 2000). Disposal options in the 1950s included incineration, composting, recycling and salvaging, and sanitary landfill. Figure 3 is a picture taken at the Tijuana dump, Mexico where people still sift through the trash looking for clothing and other items for their families (McDonald D., 2000). Economics and broad geographical flexibility made the sanitary disposal of garbage on the land the disposal option of choice. It was also clear that improved land disposal techniques, in addition to removing smoke, could eliminate mosquitoes, flies, rats and any potential disease spread by feeding garbage to swine.

It is not clear as to when burying garbage became an idea. Some say that the first written description of the sanitary landfill concept can be found in the Bible. Literature dating back to 1929 includes an article on garbage disposal by “sanitary fill”. It was learned early on that covering garbage with soil or ash helped eliminate odors. Compaction was eventually added to the process as a means of getting more garbage into less space. Issues such as compaction requirements, densities to be achieved, frequency and depth of cover placement, and limited access were not originally a part of the sanitary-landfill construction procedure requirements.

The US Army research presented the art of sanitary landfilling with several valuable contributions, including the recognition of the flexibility of a sanitary landfill, and the application of equipment still in use in sanitary landfill construction today.

The four loosely categorized classes of sanitary landfills are:

- Secure landfill – tends to entomb waste, postponing any environmental impact to the future when environmental controls and safeguards fail;
- Monofill – accepts waste that cannot be processed through resource recovery, composting, or incineration. These materials tend to be inert and may be more easily assimilated by the environment. The monofill is currently used for disposal of combustion ash, construction and demolition debris, and yard waste;
- Reusable landfill – permits excavation of the landfill contents to recover metals, glass, plastics, other combustibles, compost and potentially, the site itself following a lengthy stabilization period;
- Bioreactor landfill – is operated in a manner to minimize environmental impact while optimizing waste degradation processes. Enhanced microbial processes are used to transform and stabilize the readily and moderately decomposable organic waste constituents within 5 to 10 years of bioreactor process implementation. The bioreactor

landfill significantly increases the extent of organic decomposition, conversion rates and process effectiveness, over what would otherwise occur within a secure landfill. Stabilization means that the environmental performance measurement parameters (landfill gas composition, generation rate, and leachate constituent concentrations) remain at steady levels, and should not increase in the event of any partial containment system failures beyond 5 to 10 years of bioreactor process implementation (Reinhart D.R. and Townsend T.G., 1998).

Figure 1 Memphis, TN, 1878, Garbage collection was with small wooden carts pulled by mules (Solid Waste Management, 2000)

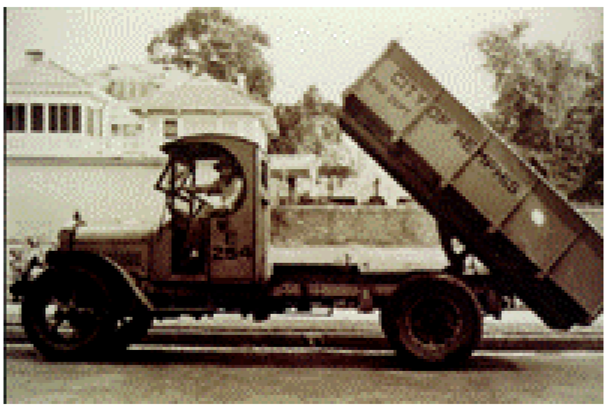


Figure 2 Memphis, TN, 1930s, Mules were replaced by simple motorized dump trucks with no compacting capability (Solid Waste Management, 2000)

Figure 3 Tijuana Dump, Mexico, 2000 (McDonald D., 2000)

Landfill and Bioreactor Regulations

Present regulations encourage landfills to remain relatively dry. In most cases, the final moisture content remains close to that of the entering waste. Figure 4 shows a typical design of a modern sanitary landfill (Reinhart D.R. and Townsend T.G., 1998).

The Federal Code most pertinent to liquid addition is 40 CFR 258.28 (see Federal Register Chapter 40, 258 Appendix), which allows re-introduction of leachate and condensate into Subtitle D lined landfills. Some states interpret 40 CFR 258.28 to mean that liquid addition, other than leachate and condensate, are not allowed into landfills. Federal Code may be interpreted to prohibit the addition of “bulk liquid wastes”, and not “amendments”, to landfills. Thus water and other amendment additions to landfills appear permissible within regulations. For example, the US Environmental Protection Agency (EPA) Region 10, approved an amendment to Washington State’s solid waste regulation that specifically allowed water addition in a controlled manner to a specific composite lined, subtitle D Landfill.

The bioreactor and leachate re-circulating landfills differ from the “dry” Subtitle D landfills in that they each receive managed liquid additions to augment waste stabilization. The bioreactor landfill differs from the leachate re-circulating landfill in that it can obtain rapid and complete stabilization by use of water and other amendments. For the bioreactor landfill, water is clearly not a waste but an amendment. Other potential bioreactor additions such as sludge and nutrients could be categorized as amendments. Federal Code is open to necessary amendments providing that other statutory constraints are met (e.g. leachate head limits on the base liner and inclusions of a single composite liner).

Favorable federal policy toward the bioreactor landfill has begun to develop as seen by Action Item 37 of the Federal Climate Change Action Plan of 1993. The following relevant recommendations were made: (Pacey J. et al., 1999)

- Creation of a joint state / federal coordination program to facilitate siting / permitting of enhanced recovery (i.e. bioreactor) landfills.
- Modification of environmental performance standards and regulatory requirements to remove unnecessary barriers to bioreactor landfills.

Municipal solid waste (MSW) landfills will also have to follow a new US EPA regulation emission limit, if their state has not yet implemented a plan. On Nov 8 1999, the EPA issued a final rule setting guidelines for existing MSW landfills where state or American Indian tribal plans are not in effect. Plans address emissions limits, compliance schedules, testing and monitoring requirements, and record keeping and reporting requirements. They also establish a process for the EPA or state to review design plans for site-specific gas collection and control systems. In 1996, the EPA issued performance standards for new MSW landfills and guidelines for existing ones with more than 50 mega-grams of volatile organic compounds (VOCs). The agency followed up with amendments in June 1998 and February 1999, requiring states, territories, localities and tribes to submit plans to the EPA. The new rule may affect more than 3,800 landfills in approximately 28 states, protectorates and municipalities. The EPA has extended the guidelines to January 2000, to encourage states in this process (Duff S., 1999).

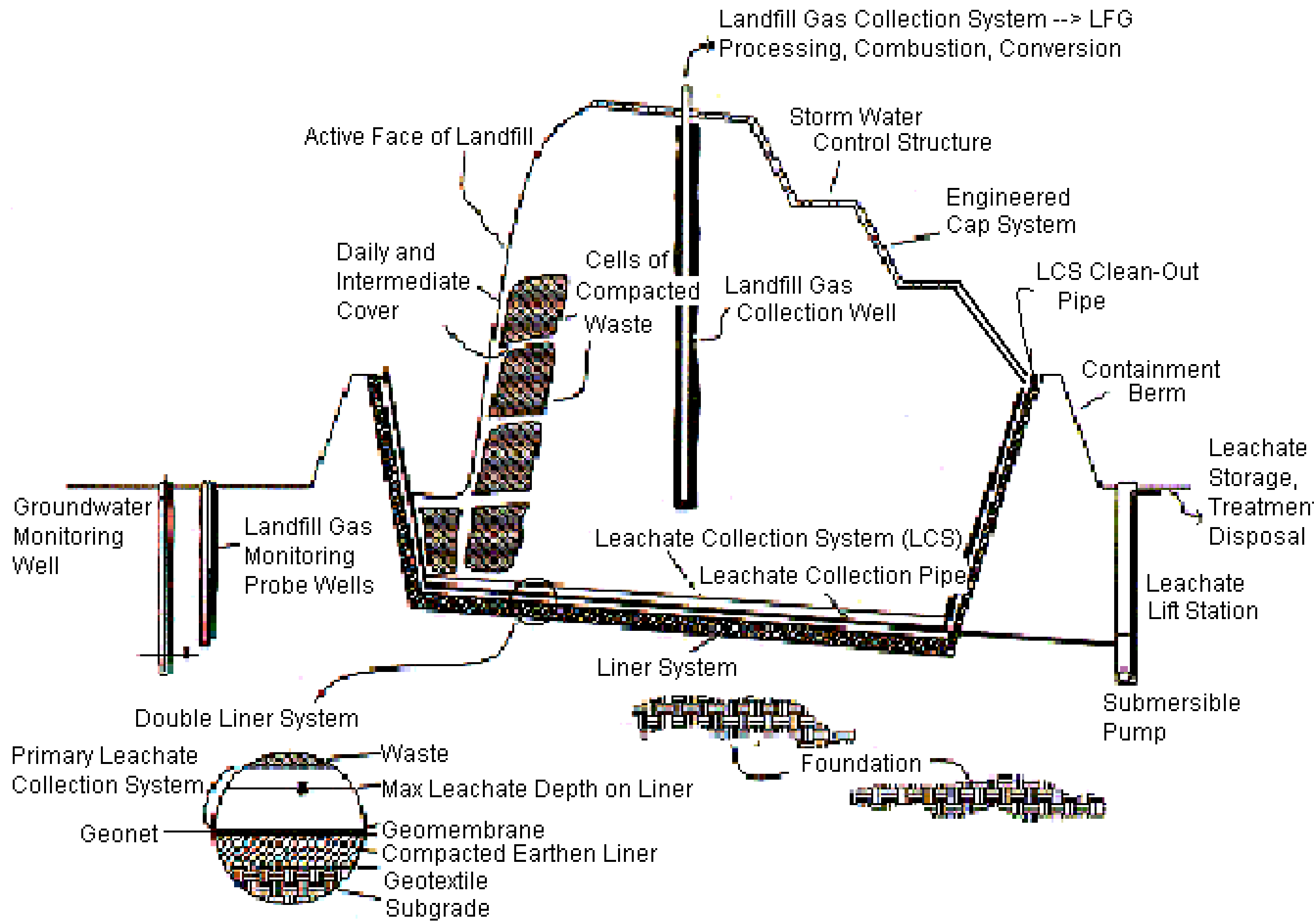


Figure 4 Typical Design of Modern Sanitary Landfill (Reinhart, D.R. and Townsend, T.G., 1998)

Objectives of this Research

Evaluate the current procedures that are followed at Denton's landfill and through literature review and the use of the Hydrologic Evaluation of Landfill Performance (HELP) model, determine the feasibility of a bioreactor landfill operation, at the same site.

Research Considerations

Determine whether leachate, climatic and soil data for the City of Denton's landfill supports the concept of bioreactor methodologies for the processing of Municipal Solid Waste.

CHAPTER 2

WASTE STABILIZATION PROCESS

Composition of Municipal Solid Waste

Municipal Solid Waste (MSW) is a term used to refer to the nation's discarded resources. It includes waste such as durable goods, non-durable goods, containers and packaging, food scraps, yard trimmings and miscellaneous inorganic wastes from residential, commercial, institutional and industrial sources. Examples of waste from these categories include appliances, automobile tires, newspapers, clothing, boxes, disposable tableware, office and classroom paper, wood pallets, and cafeteria waste (Brady P., 2000).

MSW composition is a function of the population demography. Composition affects leachate quality, landfill gas composition and quality, waste degradation rates, and resource recovery potential. It is therefore necessary to control and monitor biological, chemical, and hydrologic processors occurring within the cell (A portion of the landfill that receives waste for 2-5 years, see Denton Landfill Site Plans Appendix) to successfully operate a bioreactor landfill (Reinhart D.R. and Townsend T.G., 1998).

Denton's per capita disposal rate is higher than both the national and state rates. Table 1 shows the fiscal year tonnage and volume of solid waste that was buried at Denton's Landfill from 1996 - 2000 (Roberts E.M., 2000). In 1997, the EPA reported that 197 million tonnes of municipal solid waste were generated in the U.S.A., or an average of 2 kg per person per day. According to the Texas Natural Resource Conservation Commission (TNRCC), in 1994, permitted MSW landfills reported a total of 19,784,133 tonnes of waste disposed of in Texas. With an estimated population of 18,378,185, the per capita disposal rate was about 2.9 kg per day (Brady P., 2000). Denton's per capita disposal rate for 1999 was about 3.4 kg per day. Figure 5 depicts Denton's total tons landfilled from October 1995 through September 2000 (Roberts E.M., 2000). Figure 6 shows Denton's future growth plan, which will impact the composition of the waste stream and therefore the decomposition rates of the material in the bioreactor cells, as will Denton's future population, as shown in Figure 7 (Planning and Development Department, 1999). Table 4 summarizes Denton residential construction activities during 1999 and 2000. Greater detail can be found in the Denton Residential Subdivision Construction Activity Appendix, describing this strong growth.

A multi-year solid waste characterization study was performed (Brady P., 2000) during 1999/2000. The material was categorized as follows:

RESIDENTIAL:

- Individual Single-Family Residences that have residentially collected bags
- Mobile Home Parks
- Apartment Complexes
- Multi-Family Dwellings with commercial collected containers
- University Dormitories
- Individual Residences on Rural Route Roads collected commercially

Waste in this category was expected to contain a lesser amount of paper, but a larger amount of items such as food waste, textiles, glass, plastic and non-ferrous metals.

OFFICE:

- Financial Institutions
- Office Buildings
- Real Estate Offices
- Most University Buildings (Excludes Dormitories and Cafeterias)
- Schools
- Pre-Schools
- Wholesale Establishments

Waste in this category was expected to contain primarily high grade office paper.

RESTAURANT:

- Dine-In Restaurants
- Fast-Food Establishments
- Bowling Alleys
- Movie Theaters
- Skating Rinks

Includes businesses not listed above whose waste was expected to be primarily food, paper and plastic.

INDUSTRIAL:

- Auto Repair Shops
- Plant Nurseries
- Junk/Salvage Yards
- Sheet Metal Shops
- Paint Stores
- Chemistry Buildings or Physical Plants on Campuses

- Tire Shops
- Repair Shops

Waste in this category was expected to contain larger amounts of metals and chemical materials and a lesser amount of food, high-grade paper or plastic.

GROCERY:

- Grocery Stores
- Convenience Stores (excludes those attached to auto repair facility)

Waste in this category was expected to contain primarily cardboard, plastic, glass bottles and food discards

RETAIL:

- Business receiving merchandise for resale
- Storage Facilities
- Mall Businesses
- Thrift Stores

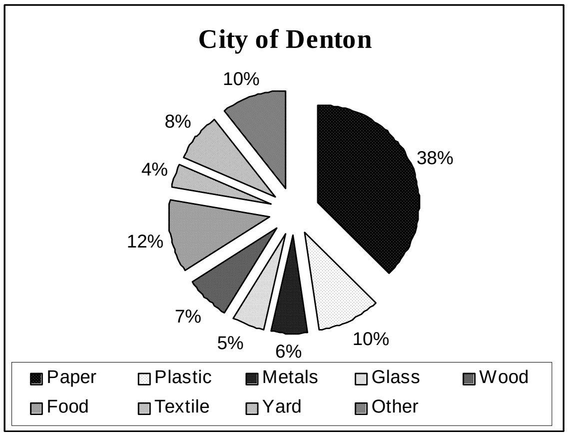
Includes businesses not mentioned above whose waste was expected to be primarily cardboard, high grade paper and miscellaneous.

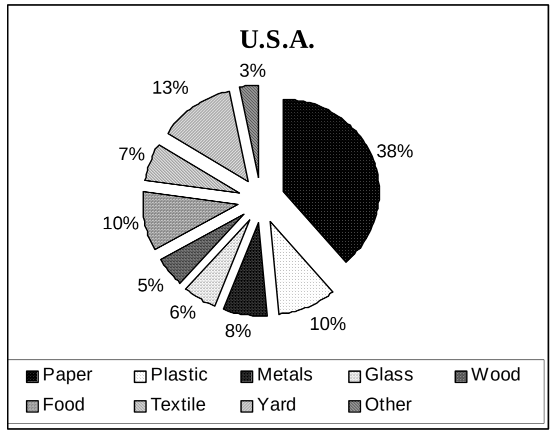
The observed distribution of materials in Denton's waste stream, Table 2, was not significantly different than the expected national distribution of materials (Brady P., 2000).

Preprocessing of waste does permit some control of the composition of the landfilled MSW. Denton does practice a limited form of preprocessing, in that the residential single family dwellings have their yard trimmings collected separately and diverted to a mulching operation. A more uniform waste stream would be created if separation of inert and organic waste, bag opening, and household hazardous waste removal was provided. This would improve leachate and gas quality, equalize subsidence (facilitating post-closure care), and simplify landfill operations. Physical properties of MSW provide some opportunity for control. These properties include in-place density and particle size, which primarily influence moisture routing within the landfill. In-place density can be controlled by compaction in the field or by baling the waste before landfilling. Table 3 depicts Denton's landfill compaction rates. Greater compaction (and resulting greater density) has advantages associated with more efficient use of air space, reduced settlement, and reduced cover material requirements. Denton Landfill Monthly Operations Appendix describes detailed usage of airspace and cover materials (Ball C., 2000). Hydraulic conductivity is diminished, moisture distribution is impaired and leachate short-circuiting is promoted as in-place density increases; therefore leachate strength may be relatively weak, resulting in delayed waste degradation. Successful bioreactor operations require reduced compaction to promote even leachate distribution, resulting in increased settlement rates. Shredding waste before placement can reduce particle size. Shredding also promotes a more uniform waste, reducing fire potential and blowing materials. It improves water distribution and promotes more equitable settlement. Additionally, more waste is exposed to microbial activity and consequently biodegradation is enhanced (Reinhart D.R. and Townsend T.G., 1998).

Fiscal Year	Residential		Commercial		Cash		Contract		City Depts		TOTAL	
Total	m3	tonne	m3	tonne	m3	tonne	m3	tonne	m3	tonne	m3	tonne
1995	43,706	15,276	248,412	49,233	32,259	11,109	13,639	4,853	1,197	354	339,214	80,825
1996	43,849	15,369	238,378	50,259	27,378	10,661	7,018	2,451	2,093	662	318,717	79,401
1997	43,857	17,124	270,001	63,929	23,740	9,672	6,601	2,270	1,748	481	345,947	93,476
1998	46,085	17,315	274,772	63,273	23,969	10,463	4,946	1,475	2,260	968	352,032	93,494
1999	48,612	20,367	303,771	68,987	14,930	6,590	4,844	1,748	4,855	3,818	377,011	101,510
2000	52,280	20,516	306,525	68,950	17,975	8,256	4,723	2,132	4,729	1,593	386,232	101,448

Table 1 City of Denton Landfilled Solid Waste (Roberts, E.M., 2000)





	Paper	Plastic	Metals	Glass	Wood	Food	Textile	Yard	Other
Denton	37.9	10.0	5.8	4.8	7.3	12.1	3.7	8.0	10.4
U.S.A.	38.6	9.9	7.7	5.5	5.3	10.1	6.8	12.8	3.3

Table 2 Observed and Expected Frequencies (%) from Materials Generated in MSW by Weight, 1999 (Brady, P., 2000)

Month Year	Compaction with Soil Cover	Compaction Waste only
May 1999	965	911
Sep 1999	990	949
Oct 1999	740	631
Dec 1999	838	756
Jan 2000	713	619
Feb 2000	599	501
Mar 2000	771	702
Apr 2000	720	675
May 2000	866	797
Jun 2000	885	835
Jul 2000	825	767
Aug 2000	904	845
Sep 2000	894	834
Oct 2000	912	861
Average	830	763

Table 3 Denton landfill monthly compaction calculated, kg per m3 (Ball C., 2000)

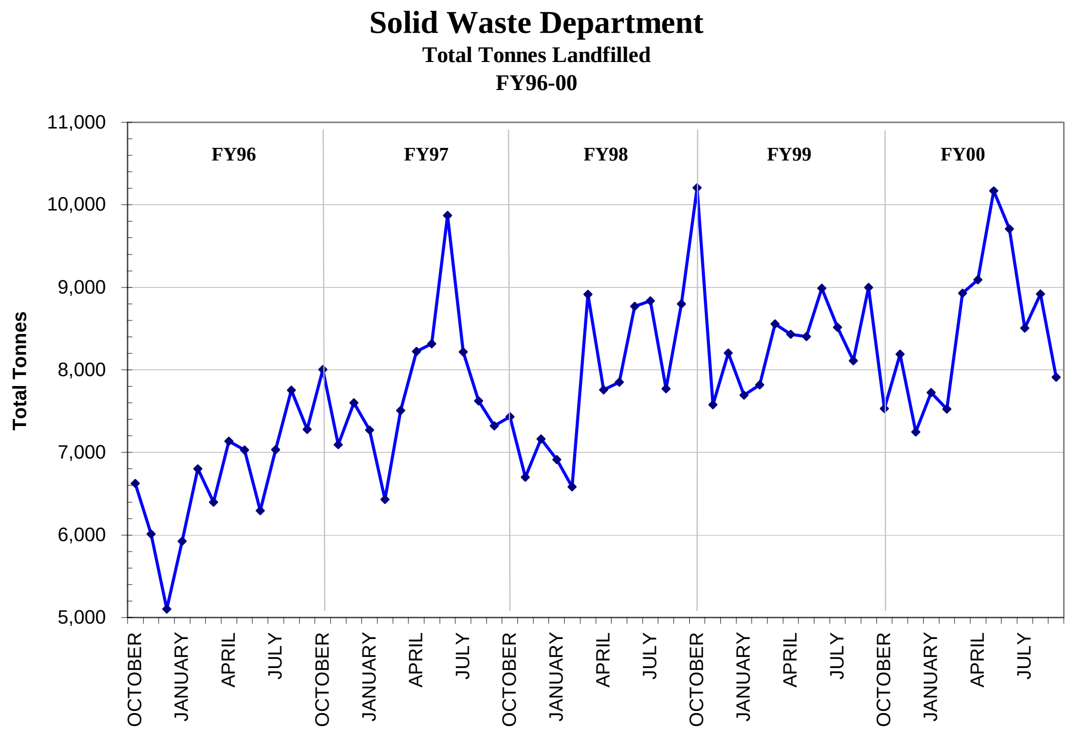


Figure 5 City of Denton Total Tonnes Landfilled (Roberts, E.M., 2000)

Residential Construction Activities	Sep 1999	Oct 2000
Number of Platted Lots	2,369	2,986
Number of Unreleased Vacant Lots	206	149
Number of Vacant Lots Available for Construction	1,169	963
Number of Lots Under Construction	342	593
Lots with Completed Houses Ready for Occupancy	652	1,281

Table 4 Denton Residential Construction Activities (Planning and Development Department, 1999)

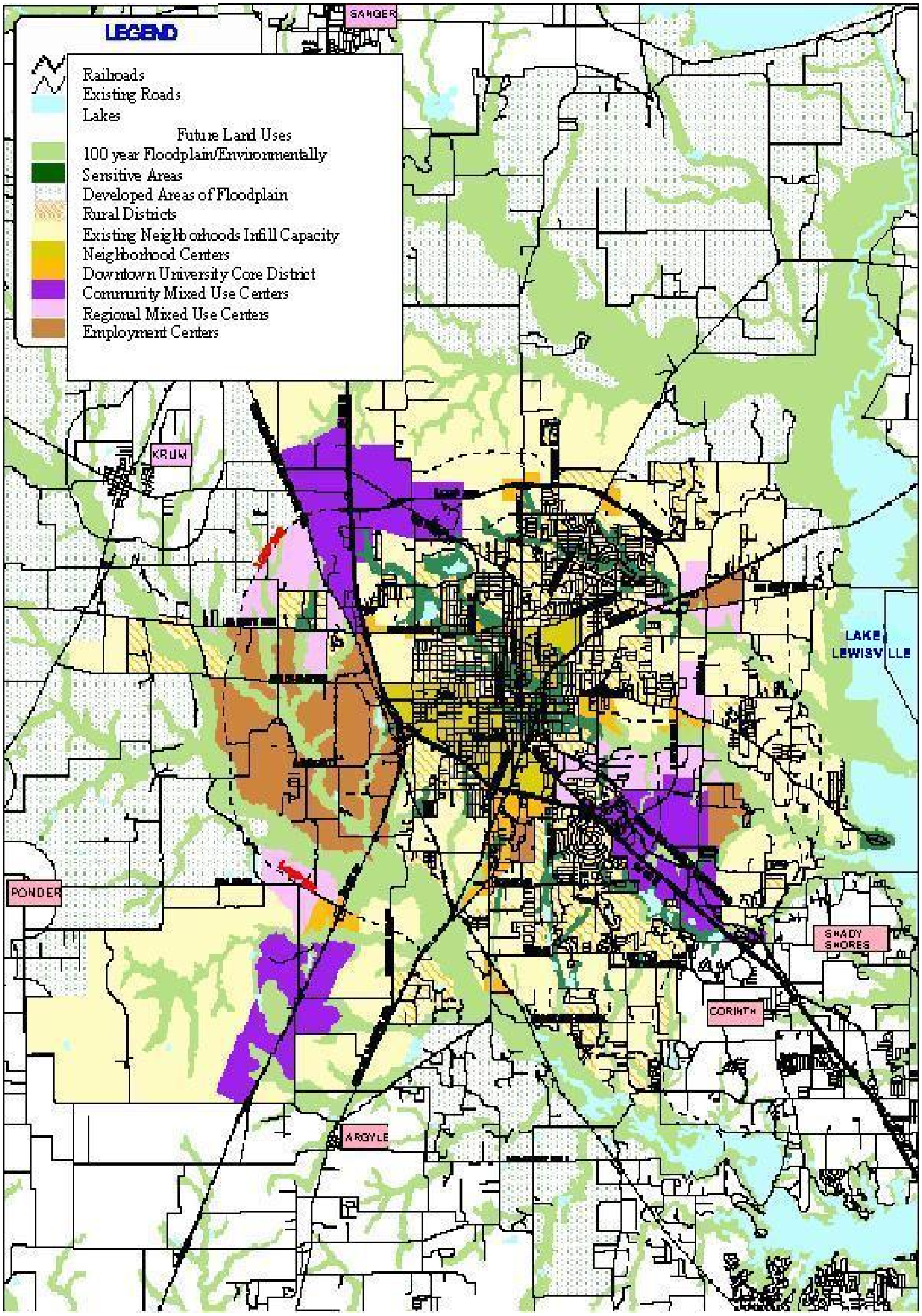


Figure 6 City of Denton Future Land Use Plan 1999-2020 (Planning and Development Department, 1999)

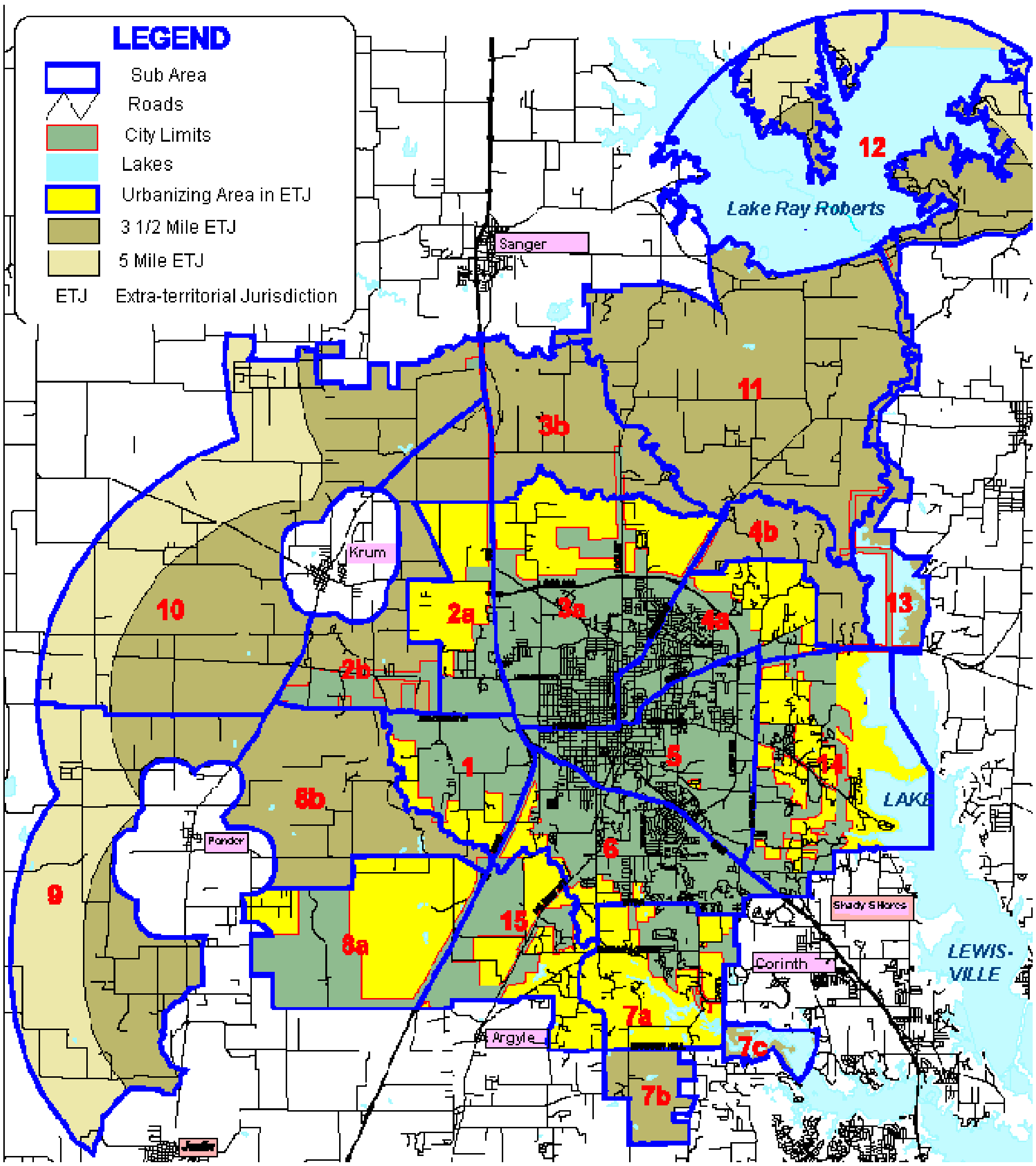


Figure 7 Population Forecasts (1999-2020) by Sub-Area (Planning and Development Department, 1999)

Environmental Factors Affecting Waste Stabilization

Oxidation reduction (redox) conditions within the landfill establish waste degradation pathways. Aerobic landfilling is more closely related to today's composting operations but it should be noted that the presence of air in a landfill may increase fire potential, has additional operating costs associated with provision of air, and may still produce gases that require collection and treatment. Anaerobic degradation, however, leads to the production of methane (60%), carbon dioxide (45%) and other trace gases. The methane can be recovered for energy generation (Hermansson E. and Nelson S., 2000). Anaerobic degradation pathways are available for many compounds that are not amenable to aerobic degradation – e.g. chlorinated aliphatic hydrocarbons.

Moisture within the landfill serves as a reactant in the hydrolysis reactions. It transports nutrients and enzymes, dissolves metabolites, provides pH buffering, dilutes inhibitory compounds, exposes surface area to microbial attack, and controls microbial cell swelling (Reinhart D.R. and Townsend T.G., 1998).

Because waste degradation involves biochemical reactions, the rate of degradation tends to increase with temperature. The temperature within a landfill cell is determined through a balance between heat production during the biological degradation of organic waste fractions and the loss of heat to the surrounding soils and atmosphere. The microbial processes are capable of significant heat generation, particularly at higher moisture conditions. Microorganisms have a temperature range over which they function best, and are loosely characterized as phychrophilic (ability to grow at 0°C), mesophilic (optimal growth at 25-40°C) or thermophilic (optimal growth above 45-50°C). Many methanogens are mesophilic (Weber-Shirk M., 2001). Temperature control at full-scale landfill cells may be difficult to achieve from an economic standpoint. Sweden's experimental "Energy Loaf" controls temperature by re-circulating heated leachate (Hermansson E. and Nelson S., 2000). Introduction of air and the consequential onset of aerobic activity serves to rapidly increase temperature and inhibit methane productionas seen at the pilot-scale experiment at Baker Place Road Landfill, Columbia County, Georgia (Hudgins M. and Harper S., 1999).

Nutrient requirements of the waste are generally met at least during the early degradation phases. Optimum pH for methanogens is 6.8-7.4. Buffering could best be used in response to changes in leachate characteristics (i.e. a drop in pH or increase in volatile organic acid -VOA concentration) in conjunction with leachate re-circulation. However, careful operation of the landfill bioreactor, initially through slow introduction of leachate should minimize the need for buffering (Reinhart D.R. and Townsend T.G., 1998).

Climatic, Figure 8, conditions have a marked effect on the working face (surface), and thus the degree of degradation under natural conditions (Unedited Local Climatological Data, WBAN 03991 2000). Denton uses a tarp to cover the working face daily, and clayey soil, as the intermediate cover. The clayey soil is from cell excavations and is a composite of the Woodbine noncalcareous shale and sandstone and Grayson Marl calcareous shale (Hunt W.C., 2000).

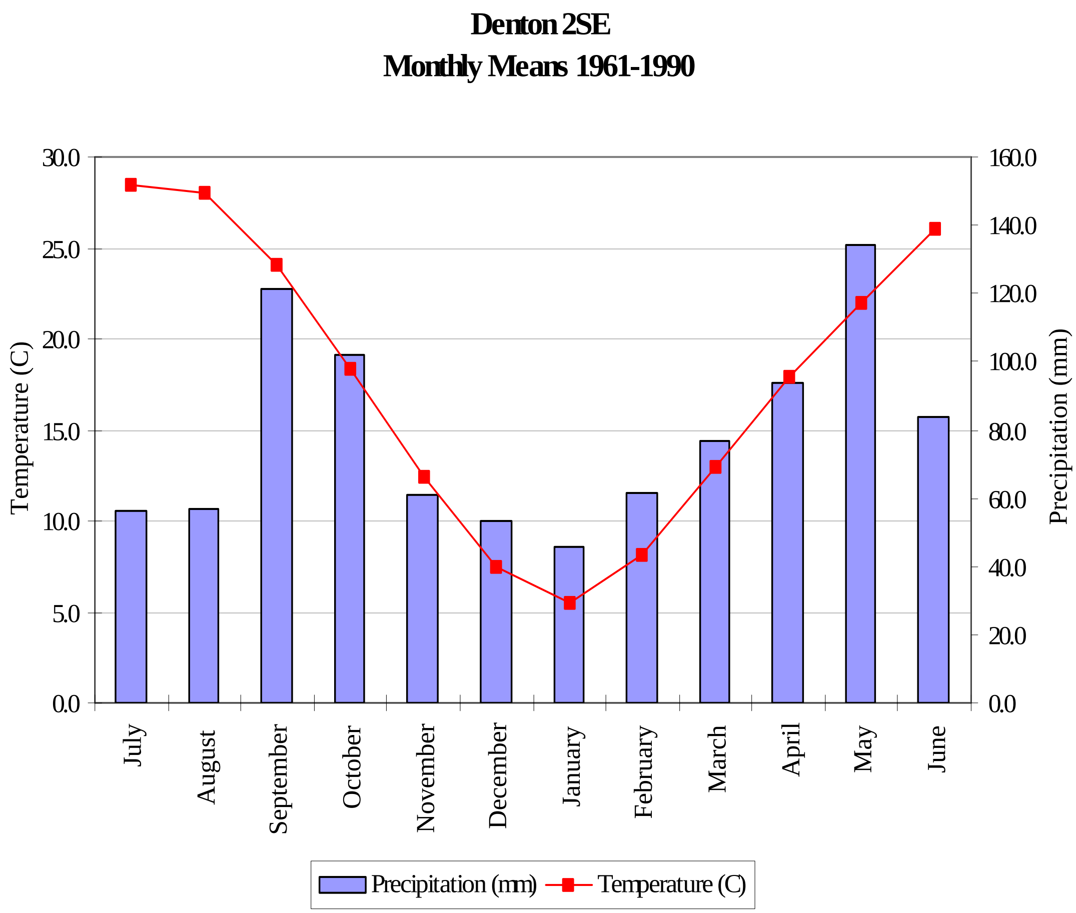


Figure 8 Denton 2SE Station Mean Monthly Temperatures and Precipitation 1961-1990 (Unedited Local Climatological Data, WBAN 03991 2000)

Five Phases of Landfill Stabilization

Landfill investigation studies suggest that the stabilization of waste proceeds in five sequential and distinct phases (Pohland F.G. and Harper S.R.,). The rate and characteristics of leachate produced and biogas generated from a landfill vary from one phase to another and reflect the processes taking place inside the cell, as shown by the graph in Figure 9. These phases tend to overlap due to the lengthy period of waste placement.

The initial adjustment phase (Phase I) is associated with initial placement of solid waste and accumulation of moisture within cells. An acclimation period, or lag time, is observed until sufficient moisture develops to support an active microbial community. Preliminary changes in environmental components occur in order to create favorable conditions for biochemical decomposition. The lag time in the graph is recorded as negative stabilization days due to the oxidizing environment.

Phase II, the transition phase, field capacity is often exceeded, and a transformation from aerobic to anaerobic occurs. This is evidenced by the depletion of oxygen trapped within the landfill media. A trend toward reducing conditions is established in accordance with shifting of electron acceptors from oxygen to nitrates and sulphates, and the displacement of oxygen by carbon dioxide. By the end of this phase, measurable concentrations of chemical oxygen demand (COD) and volatile organic acids (VOA) can be detected in the leachate. Anaerobic conditions are recorded as positive stabilization days in the graph.

In the acid formation phase (Phase III), the continuous hydrolysis (solubilization) of solid waste, connected with microbial conversion of biodegradable organic content, produces intermediate VOAs at high concentrations. A decrease in pH values is often observed accompanied by metal species mobilization. Viable biomass growth associated with the acidogenic bacteria (acid formers), and rapid consumption of substrate and nutrients are the predominant features of this phase.

During the (Phase IV) methane fermentation process, intermediate acids are consumed by methanogenic bacteria and converted to methane and carbon dioxide. Sulphate is reduced to sulphide. The pH value is elevated, being controlled by the bicarbonate buffering system, and consequently supports the growth of methanogenic bacteria. Heavy metals are removed from the leachate by complexation and precipitation and transported to the solid phase.

During Phase V, the final state/ maturation phase of the landfill, nutrients and available substrate become limited and the biological activity shifts to relative dormancy. Gas production drops dramatically and leachate strength remains constant at much lower concentrations than earlier phases. Because gas production has almost ceased, atmospheric gases may permeate back into the landfill, and oxidized species may slowly appear. The slow degradation of resistant organic fractions may continue with the production of humic-like substances.

The progress toward final stabilization of solid waste is subject to physical, chemical, and biological factors within the landfill environment, the age and the characteristics of landfilled waste, the operational and management controls applied, as well as the site-specific external conditions, as mentioned earlier.

Characteristics of Leachate

Material is removed from the waste mass via mechanisms that include leaching of inherently soluble material, leaching of soluble products through biological and chemical transformation, and washout of fines and colloids. The characteristics of leachate are highly variable depending on the composition of the waste, rate of water infiltration (Figures 12 and 13), refuse moisture content, and landfill design, operation and age, Table 5.

Organic contaminants of leachate are primarily soluble refuse components or decomposed products of biodegradable waste. The organic compounds found at highest concentration in leachate is generally VOAs that are produced during the decomposition of lipids, proteins, and carbohydrates. Aromatic hydrocarbons, including benzene, various xylenes, and toluenes are frequently found at lower concentrations. These compounds were considered to be constituents of gasoline and fuel oils. A total of 150 different organic compounds have been identified in multiple studies, however only 29 were identified in more than one, concluding that leachate composition was quite site specific (Reinhart D.R. and Townsend T.G., 1998). Denton's landfill leachate analysis will be conducted annually beginning 2001.

The dominant organic class in leachate shifts, as the age of the landfill increases due to the ongoing microbial and physical/chemical processes within the landfill. An investigation of leachates obtained from landfills operated from one to twenty years found that the abundance of high molecular weight, humic-like substances decreases with age, while intermediate-sized fulvic materials showed significantly smaller decreases. The relative abundance of organic compounds present in these leachates was observed to decrease with time in the following order: free VOAs, low molecular weight aldehydes and amino acids, phenolic compounds and fulvic acids.

A variety of heavy metals are frequently found in landfill leachates including zinc, copper, cadmium, lead, nickel, chromium, and mercury. These metals are either soluble components of the refuse or are products of the physical processes such as corrosion and complexation. In several instances heavy metal concentrations in leachate exceed US Toxicity Characteristic Leaching Procedure standards. Heavy metal concentrations in leachate do not appear to follow patterns of organic indicators such as COD, BOD, nutrients, or major ions. Heavy metal release is a function of characteristics of the leachate such as pH, flow rate and the concentration of complexing agents (Reinhart D.R. and Townsend T.G., 1998).

Leachate Treatment and Disposal

The simplest approach to managing leachate involves discharge to a local wastewater plant. If a sewer connection is located at the landfill site, leachate may be directly discharged from the leachate storage facility (Reinhart D.R. and Townsend T.G., 1998). The volume of leachate is normally far lower than wastewater, but it exhibits large variations in quantity and quality, and at times contains high concentrations of potentially disruptive chemicals. Natural treatment operations such as wetlands have been used in some cases to polish leachate before discharge (Castonguay N. et al., 2000).

Construction is underway (2001) to connect the leachate collection system with the sewer system for Denton's landfill. Regular monitoring of leachate composition will be performed to ensure acceptable incoming toxicity levels to be treated by Denton's Waste Water Plant.

Characteristics and Generation of Landfill Gas

When solid waste decomposes, significant portions of organic wastes are ultimately converted to gaseous end-products. The rate of gas production is a function of: refuse composition, climate, moisture content, particle size and compaction, nutrient availability, and buffering capacity. Reported production rates vary from 0.12-0.41 m^3/kg dry waste (Reinhart D.R. and Townsend T.G., 1998). Production rates and gas composition follow typical stabilization phases with peak flow rates and methane content occurring during the methanogenic phase. Landfill gas is typically 40-60% methane with carbon dioxide and trace gases such as hydrogen sulphide, water vapor, hydrogen and various VOCs comprising the balance. Because of their high vapor pressures and low solubilities, many toxic VOCs are observed in landfill gas.

Landfill Gas Control

Gas collection is conducted to minimize emissions to the atmosphere for health and safety concerns, aesthetics and to minimize atmospheric degradation. Typical gas collection systems utilize vertical wells placed within the landfill at the time of closure. These wells are similar to those used for groundwater and consist of perforated pipe surrounded by a permeable media such as gravel (Reinhart D.R. and Townsend T.G., 1998). Gas will migrate to a well due to the pressure difference between the landfill interior and the atmosphere. Passive venting does not always result in large collection efficiencies. The “Energy Loaf” has perforated horizontal pipes connected to the vertical wells in a patented design, enhancing gas collection efficiencies (Hermansson E. and Nelson S., 2000).

Tier II testing (Maas J., 1997) was completed at Denton's Landfill during 2000. As a result of these low emissions, regulations do not require a gas collection system design or installation be considered for another 5 years.

Waste Decomposition and Landfill Settlement

The heterogeneous nature of MSW and the different degrees of stabilization that occur in a landfill cell, rarely result in uniform settlement. This differential settlement must be considered in the design of the landfill gas collection manifolds and the surface capping system (Reinhart D.R. and Townsend T.G., 1998).

Denton's Landfill Phase 1a will have a design for closure prepared and constructed during 2001. MSW permitted volume for this cell has been reached, and as a result the waste is now being received in the Phase 2 cells.

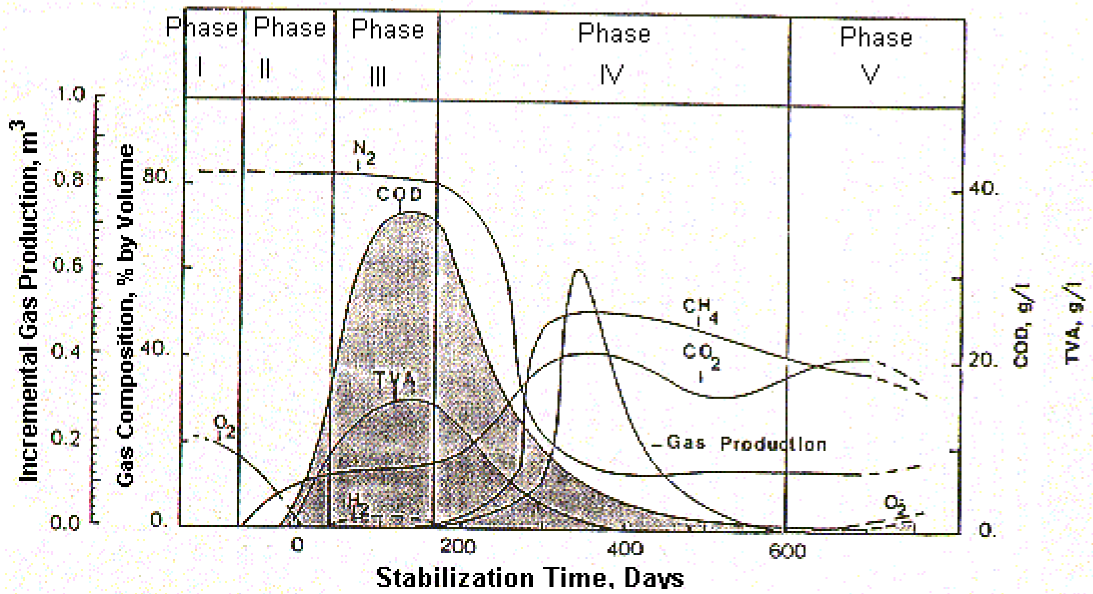


Figure 9 Five Phases of Landfill Stabilization, (Tchobanoglous G. et al., 1992b)

Parameter	Phase II Transition	Phase III Acid Formation	Phase IV Methane Formation	Phase V Final Maturation
BOD, mg/l	100-10,000	1,000-57,000	600-3,400	4-120
COD, mg/l	480-18,000	1,500-71,000	580-9,760	31-900
TVA, mg/l as Acetic Acid	100-3,000	3,000-18,800	250-4,000	0
BOD/COD	0.23-0.87	0.4-0.8	0.17-0.64	0.02-0.13
Ammonia, mg/l -N	120-125	2-1,030	6-430	6-430
pH	6.7	4.7-7.7	6.3-8.8	7.1-8.8
Conductivity, µmhos/cm	2,450-3,310	1,600-17,100	2,900-7,700	1,400-4,500

Table 5 Conventional Landfill Leachate Concentration Ranges as a Function of the Degree of Landfill Stabilization (Reinhart D.R. and Townsend T.G., 1998)

CHAPTER 3

LANDFILL CONTAINMENT SYSTEMS

Fifteen years ago under amendments to the Resource Conservation and Recovery Act (RCRA), Congress mandated the first multi-layered liner and cap systems (including geomembranes) for hazardous waste landfills, thereby creating the basis for "dry tomb" storage of waste. The EPA and state agencies have carried these mandates forward, with some slight alterations, into multi-layered liner and cap systems for solid waste landfills. Following separate statutory and regulatory paths under the Air Quality Analysis Workshop, EPA and state agencies have developed regulations controlling emissions of regulated gaseous materials from landfills. These regulations require passive or active systems associated with the cap system to control the release of greenhouse gases from landfills with a design capacity greater than 100,697tonnes . Modifications to the cap barrier layer as described by RCRA are permitted (Richardson G.N. and Sprague R.T., 2000; U.S. Department of Commerce, 1998).

Leachate is generated as a consequence of water coming in contact with solid waste. Leachate from MSW landfills varies in strength as a result of the biological activity occurring. Rubbish, food, garden wastes, crop and animal residues contribute to the organic material, while the inorganic constituents in leachate are often derived from ash, construction and demolition debris. Reports indicate that increased quantities of paper in solid waste result in a decreased rate of waste decomposition. Lignin, the primary component of paper, is resistant to anaerobic decomposition, which is the primary means of degradation in landfills (Reinhart D.R. and Grosh C.J., 1998). The characteristics of the leachate produced are highly variable, depending on the composition of the solid waste, precipitation rates, site hydrology, compaction, cover design, waste age, sampling procedures, interaction of leachate with the environment, and landfill design and operation. The Denton landfill currently follows the standard "dry tomb" technique, removing leachate from the landfill, through storage, and then treatment and disposal at the Denton wastewater treatment facility.

Landfill gas (LFG) results from biological decomposition of organic material in the solid waste stream. A large portion (Table 2) of the waste stream is composed of biodegradable material. For most of the landfill life anaerobic conditions dominate, with the primary by-products being methane (60%) and carbon dioxide (45%). Methane can become explosive (5-15% by volume in air) under certain conditions, as well as being considered a greenhouse gas, being 30 times more potent than carbon dioxide (Cox S., 2000). The trace components are generally toxic and have odor-causing characteristics.

Barrier Layers, Liners and Cap

Figure 10 depicts an EPA recommended landfill cap system. Modern sanitary landfills utilize barrier systems to prevent leachate from leaving the landfill and contaminating the underlying soil and groundwater, as well as preventing water from entering the landfill to create leachate. Barrier layers (see Denton Landfill Liner Details Appendix) are constructed of materials that possess low permeability to water. The most common materials include compacted soil (clay) and synthetic membranes (geomembranes). The containment layer at the bottom of the landfill is known as a liner. The one at the top is referred to as a cap. The barrier layers may conceptually be thought of as one unit, they are in reality multiple layers of different materials, thus more accurately referred to as liner and cap systems (Reinhart D.R. and Townsend T.G., 1998).

Current regulations for MSW landfills require a liner system composed of a composite liner with 60cm of compacted soil at a maximum hydraulic conductivity of 10^{-7}cm/sec and a geomembrane that must be at least 1.524mm (Wells J., 1999) thick for HDPE. The hydraulic conductivity is an engineering parameter relating the permeability of a porous media to the flow of water. Denton Landfill Liner Details Appendix shows these requirements in greater detail. The geomembrane must be in direct contact with the compacted soil. It is then overlain by a drainage layer that limits the depth of leachate on the liner to less than 30cm at all times. Other layers must be provided to permit drainage and removal of leachate away from the liner. These leachate collection systems (LCS) are composed of highly permeable materials e.g. sand, geonet, geotextile. Figure 11 depicts the installation of a geonet at Yolo County, CA (Yazdani R. et al., 2000).

The natural clay deposits, Upper Cretaceous Woodbine and Grayson Marl, (Hunt W.C., 2000) are used as landfill barriers in the Denton landfill. A number of properties make this compacted soil amenable for use as a component of the containment system. These include mechanical properties e.g. shear strength, but most importantly, the impermeability of the clay to water. This along with many other parameters is tested routinely during soil liner construction. In recent years engineered materials known as geosynthetics have been developed. One of the most common uses of geosynthetics is for the geomembrane. Denton uses high-density polyethylene (HDPE) as one of its components for the bottom liner. The liner design for a RCRA Subtitle C hazardous waste landfill requires a double liner/drainage collection system. Denton is a MSW Subtitle D landfill, therefore does not require these extra precautions and associated costs.

A cap system functions in a similar manner to a liner system, except the purpose is to keep water from entering the landfill. Regulations require closure of the cell when the permitted capacity has been reached. The capping will prevent water from entering and the reduction in gas migration. Drainage layers are also included as part of the cap system to serve as gas venting layers to facilitate gas transport to the collection wells. A vegetative layer is located above the barrier layer to prevent soil erosion, Figure 10 (Reinhart D.R. and Townsend T.G., 1998).

As the first generation of Subtitle D landfills are reaching the end of their operational life, considerable technical questions have been raised regarding both the design of and technical justification for the expensive final covers proposed for these facilities. Concerns include:

- The use of an infiltration barrier system on the 4:1 to 3:1 side slopes common to the industry has created a slope stability problem that might lead to the inevitable failure of such covers.
- Landfills that re-circulate leachate will undergo significant settlement that could damage the expensive barrier covers. Why install a barrier cover to limit surface-water infiltration if leachate is being pumped beneath the cover?
- Are barrier covers required in arid and semiarid regions of the USA?
- Are barrier covers required to meet the New Source Performance Standards (NSPS) requirements?

Having spent millions of dollars to install a liner system, most owners naturally question placement of an essentially impermeable final cover over the waste. This need is based on EPA's concern that lined landfills should not, over the long-term, become "bathtubs" that eventually fill and release leachate to the environment. Subtitle-D regulations in all states require that an interim cover be placed on waste that will not receive additional waste for more than 30 days and that the final cover be placed within one year of final waste placement (Richardson G.N. and Sprague R.T., 2000).

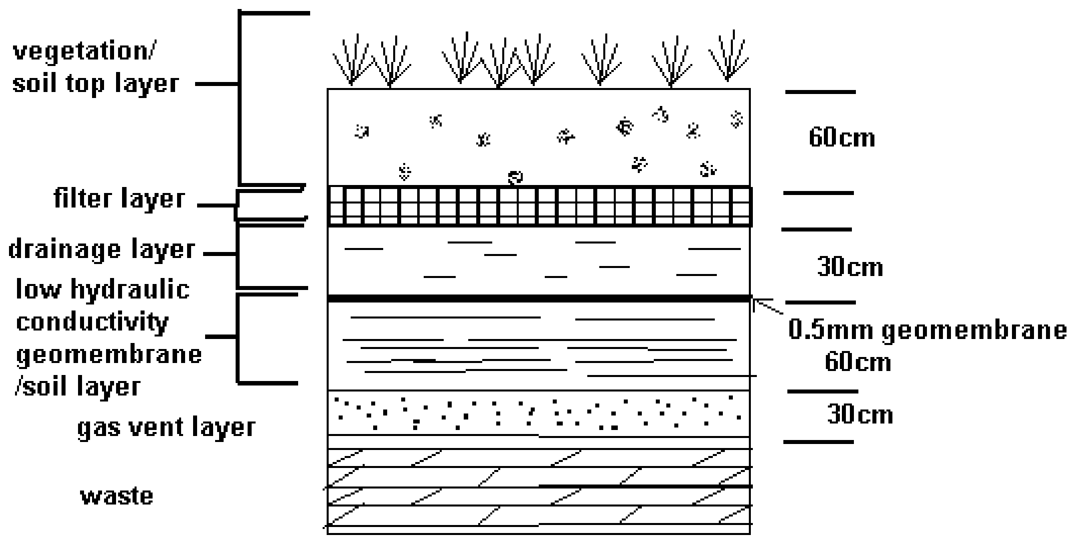


Figure 10 EPA recommended landfill cap system (Reinhart, D.R. and Townsend, T.G., 1998)

Figure 11 Placement of Geonet on the Base Liner, Yolo County, Woodland, CA (Yazdani R. et al., 2000)

Leachate Collection and Storage System

When rain falls on a landfill site, the water leaves as storm-water runoff, evaporates, transpires from the vegetation, or infiltrates into the landfill creating leachate. The infiltrate is stored (absorbed) by the landfill material, or migrates under the force of gravity, being intercepted by the liner system.

The amount of leachate generated at a landfill depends on many conditions, including site climate, landfill morphology, waste depth, landfill surface conditions, and the facility operation. Figure 12 shows a simplified water budget. A water budget analysis is a common procedure in the field of hydrology. This technique has been applied to landfills to predict leachate generation. Standard hydrologic tools are used to determine the amount of rainfall that infiltrates into the landfill for a given set of climate and site conditions. This water is stored initially in the landfilled material. Field capacity is defined as the amount of water that a permeable material such as waste may store against the force of gravity, before it drains.

The simulation of water flow through the landfill to more accurately predict the unsaturated flow conditions which typically occur is a common feature of most modeling programs. The most commonly applied landfill water budget model is the Hydrologic Evaluation of Landfill Performance.

Leachate Collection Systems (LCS) are designed to minimize the depth of leachate above the liner, per RCRA Subtitle D landfill regulations – no more 30cm depth. The collection system must be operational throughout the active phase of the landfill. For that reason the leachate collection system must be simple, safe and durable. The main components of a leachate collection system are:

- collection unit - drainage gravel layer, side drains, main drain
- transportation unit - main drain and side drains
- intake system for the collection well
- collection well, inspection wells, sampling wells, pumping wells
- discharge pipe - gravitation and pressure pipes

The leachate collection system should be designed to accommodate the maximum monthly precipitation for an average year (data from the most recent 30 years) (U.S. Department of Commerce, 1998; Danish Environmental Protection Agency, 2001). The four parameters having the greatest impact on the liner head are leachate flow rate into the LCS, permeability of the drainage layer, length of drainage path, and slope of the liner. Materials typically used in the LCS are sand, gravel or synthetic material – geonet.

Leachate drains from the LCS to a series of trenches that typically contain large diameter pipes surrounded by a blanket of gravel. The trenches themselves are sloped, and ultimately drain to a sump or lift-station. A storage system must be provided for leachate at the landfill site. Denton Landfill LCS specifications for Phase 2 are shown in Denton Landfill Liner Details Appendix.

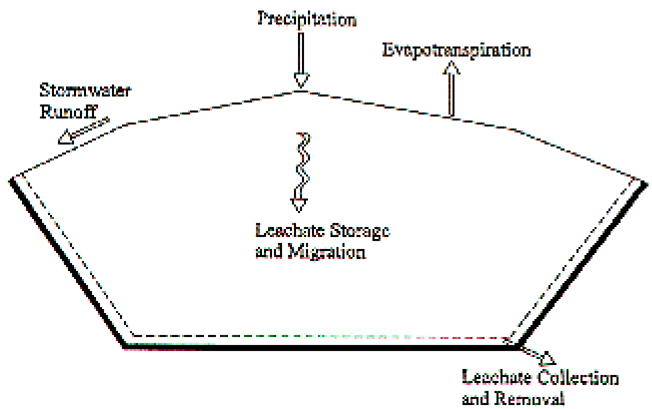


Figure 12 Landfill Water Balance (Reinhart D.R. and Townsend T.G., 1998)

Gas Collection and Control

MSW landfills possess characteristics distinct from other types of landfills as a result of the large amount of biodegradable material that is present in the waste, and the resulting decomposition or stabilization of these materials. Landfills are estimated to be the largest anthropogenic source of methane in the USA. Congress expanded the Clean Air Act in 1988 to regulate municipal solid waste landfills (MSWLFs). This control was expanded in 2000 with the enactment of New Source Performance Standards for non-methane organic compound emissions from MSWLFs (Richardson G.N. and Sprague R.T., 2000). The USA landfill-gas-to-energy industry has experienced a 10% growth per year since 1990, resulting from the economic incentives and associated programs to encourage greenhouse gas reductions and increased use of renewable energy. As of 1999 there were 300 operational facilities, 90 facilities under construction and 144 planned for construction. Landfill gas can displace natural gas and other fossil fuels in most applications. Landfill-gas-to-energy projects predominantly generate electricity (70%), utilizing reciprocating engines, gas turbines, boiler/steam turbines, combined gas/steam turbines and fuel cell technologies (Thorneloe S. et al., 1999).

CHAPTER 4

HYDRODYNAMICS OF LEACHATE RECIRCULATION

Leachate Generation and Quality

The major processes controlling leachate generation and re-circulation are depicted in Figures 13 and 14. Leachate quantity is impacted by: precipitation, type of site, groundwater infiltration, surface water infiltration, waste composition and moisture content, preprocessing of waste (no baling or shredding practiced at Denton landfill), cover design, depth of waste, climate, evaporation, evapotranspiration, gas production, and waste density. Continuous leachate production occurs once the absorptive capacity of waste has been satisfied. Leachate quantities are site specific, ranging from zero in arid regions, to nearly 100 percent of precipitation in wet climates during active landfill operation. Low quantities of leachate are produced at the Denton landfill during the rainy seasons. Leachate production reaches a peak just before cell closure and then declines significantly with the provision of surface grading and interim or final cover.

The model most frequently used to quantify the processes depicted in Figure 13, is the Hydrologic Evaluation Performance (HELP) (Reinhart D.R. and Townsend T.G., 1998).

> The HELP program is a quasi-two-dimensional hydrologic model for conducting water balance analyses of landfills, cover systems, and other solid waste containment facilities (Schroeder P.R. et al., 1994b).

The model accepts weather, soil and design data and uses solution techniques that account for the effects of surface storage, snowmelt, runoff, infiltration, evapotranspiration, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate re-circulation, unsaturated vertical drainage, and leakage through soil, geomembrane or composite liners. Landfill systems including various combinations of vegetation, cover soils, waste cells, lateral drain layers, low permeability barrier soils, and synthetic geomembrane liners may be modeled. The model facilitates rapid estimation of the amounts of runoff, evapotranspiration, drainage, leachate collection and liner leakage that may be expected to result from the operation of a wide variety of landfill designs. The primary purpose of the model is to assist in the comparison of design alternatives (Schroeder P.R. et al., 1994b). The HELP model is useful for long-term prediction of leachate quantity, but is highly inaccurate for daily predictions.

Internal storage of leachate within the landfill is an important concept both to the water balance used to calculate leachate generation rates and to the success of a leachate re-circulation system. Internal storage of leachate is possible because the moisture content of the incoming waste is generally below the absorptive capacity of the waste. Field capacity is a function of waste composition, age, density and porosity. Less than 4 percent of the total waste stream (Brady P., 2000) received by Denton's landfill, exceeds the waste field capacity. This portion refers to the restaurant waste stream.

Fungaroli and Steiner (Fungarali A.A., 1979) developed a relationship between field capacity and density, as shown in Equation 1, as well as finding that as the mean

Equation 1

$$\theta_{fc} = 0.2 \ln \left(\frac{\rho}{1.6855} \right) - 1.2$$

where: θ_{fc} = moisture content at field capacity, and

ρ = density, kg/m^3

particle size decreases, field capacity increases.

Tchobanoglous (Tchobanoglous G. et al., 1992a) reported that field capacity declines with landfill depth due to the compaction of the lower waste layers by the waste overburden, as seen by Equation 2. Hentrich reported that shredded waste has a higher moisture holding capacity (Reinhart D.R. and Townsend T.G., 1998).

Equation 2

$$\theta_{fc} = 0.6 - \left(\frac{W}{22{,}000 + W} \right)$$

where: θ_{fc} = moisture content at field capacity, and

W = overburden weight at the mid height of the waste, kg

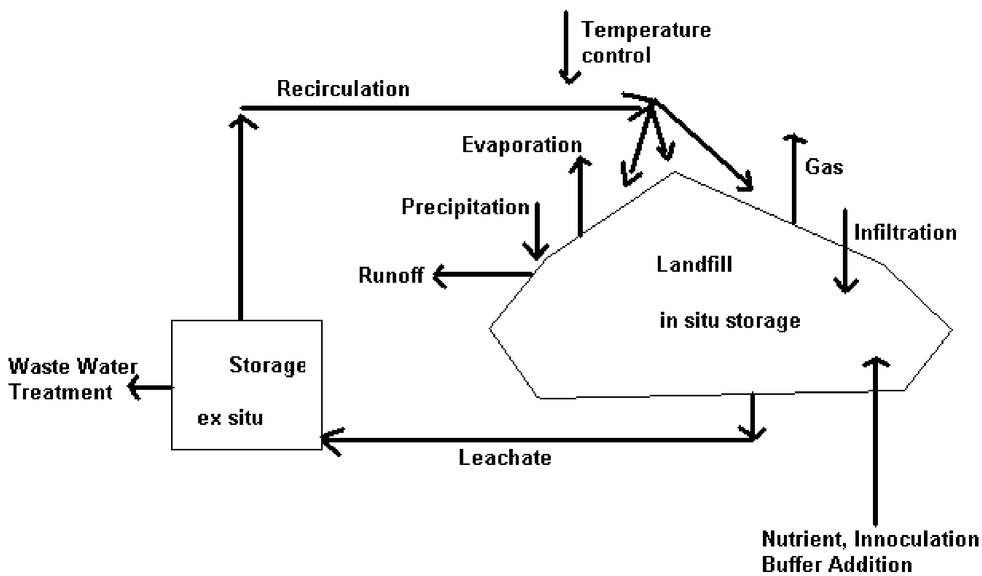


Figure 13 Schematic Landfill Bioreactor Diagram (Reinhart D.R. and Townsend T.G., 1998)

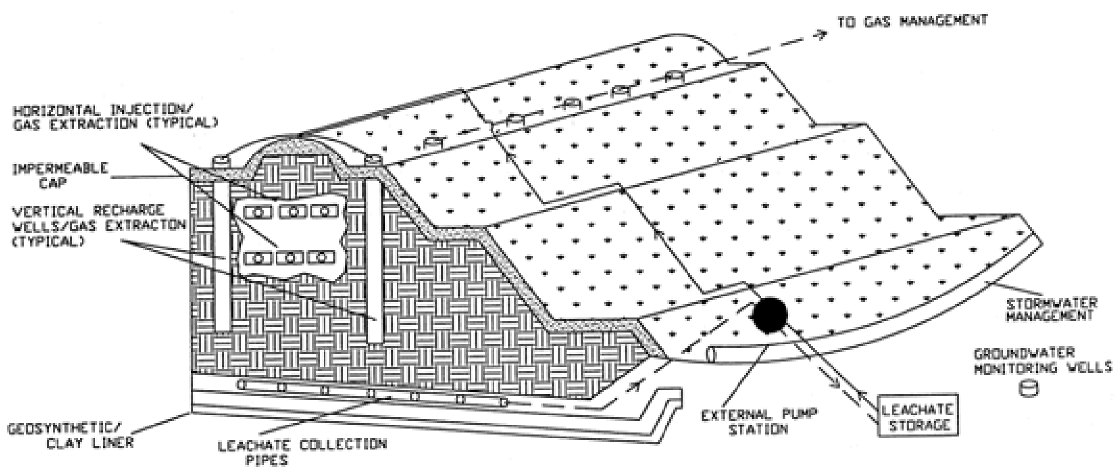


Figure 14 Wet Landfill Cell Schematic (Fiedler C., 1999)

Leachate Flow/Movement

Operating experience has shown that leachate is generated well before the model calculations predict. Leachate generation may occur before reaching field capacity as a result of uneven distribution of moisture, channeling and storm-water runoff from slopes into the leachate collection system. Figure 15 shows the processes affecting moisture movement through a landfill cell. Uneven moisture distribution is a natural consequence of unsaturated flow. However, this is exacerbated by the heterogeneity of solid waste in landfill cells. Impermeable items and the continued use of low permeable daily and intermediate cover (Denton's Landfill uses a tarp for daily cover, and soil for intermediate cover) prevent even distribution of moisture and promoting horizontal leachate movement. Gas production tends to block moisture paths in parts of the landfill during early operation. Channeling declines over time as a result of landfill settlement, as degradation of waste weakens the landfill structure and flow channels (Tchobanoglous G. et al., 1992b).

The operative processes inherent to the natural stabilization phases occurring within the landfill cell determine the fate of inorganic and organic compounds. Contaminants tend to partition among aqueous, solid, and gaseous phases of the landfill. Contaminant mobility and fate is largely determined by the magnitude of the preference for one phase relative to another, which is a function of the physical/chemical characteristics of both the contaminant and the phases present. Figure 16 depicts the transport/transformation phenomena that may affect the environmental fate of a landfilled contaminant. Mechanisms of mobility and transformation include biotransformation, volatilization, dissolution and advection, sorption, and chemical reactions e.g. precipitation, reduction, oxidation, and hydrolysis. Biotransformation and chemical reaction can reduce contaminant mass, however a more toxic and/or mobile compound may be produced. Dissolution and advection results in the movement of the compound with the bulk flow through the waste pore spaces. Volatilization and transport by the product gas can remove the more volatile contaminants from the landfill. Sorption and precipitation can retard contaminant movement as the compound interacts with the solid phase. Transport can be influenced by compound complexation or chelation, which can either retard movement if the complex becomes associated with the solid phase or enhance mobility if the compound "piggybacks" on a more soluble complexing agent.

The primary removal mechanism for metals in conventionally operated landfills appears to be washout, although limited chemical precipitation may occur. In leachate re-circulating landfills, the primary removal mechanism appears to be metal sulphide and hydroxide precipitation. Subsequent capture within the waste matrix is via encapsulation, sorption, ion exchange, and filtration. Leachate re-circulation stimulated reducing conditions in lysimeters, providing for the reduction of sulphate to sulphide, which moderated leachate metals to very low concentrations. The formation of metal sulphides under anaerobic conditions effectively eliminated the majority of heavy metals in leachate. With time, moderate to high molecular weight humic-like substances are formed from waste organic matter in a process similar to soil humification. These substances tend to form strong complexes with heavy metals. Remobilization of precipitated metals can occur from complexation once the organic content has been stabilized and aerobic conditions begin to re-establish. This supports the idea of inactivating the landfill (removing all moisture) once the waste is sufficiently stabilized (Reinhart D.R. and Townsend T.G., 1998).

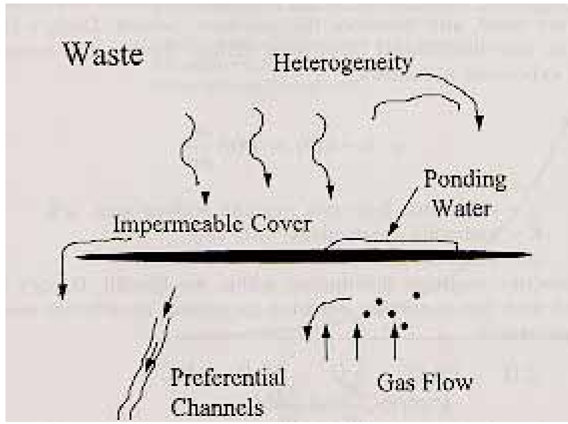


Figure 15 Process Affecting Leachate Movement Through a Landfill (Reinhart D.R. and Townsend T.G., 1998)

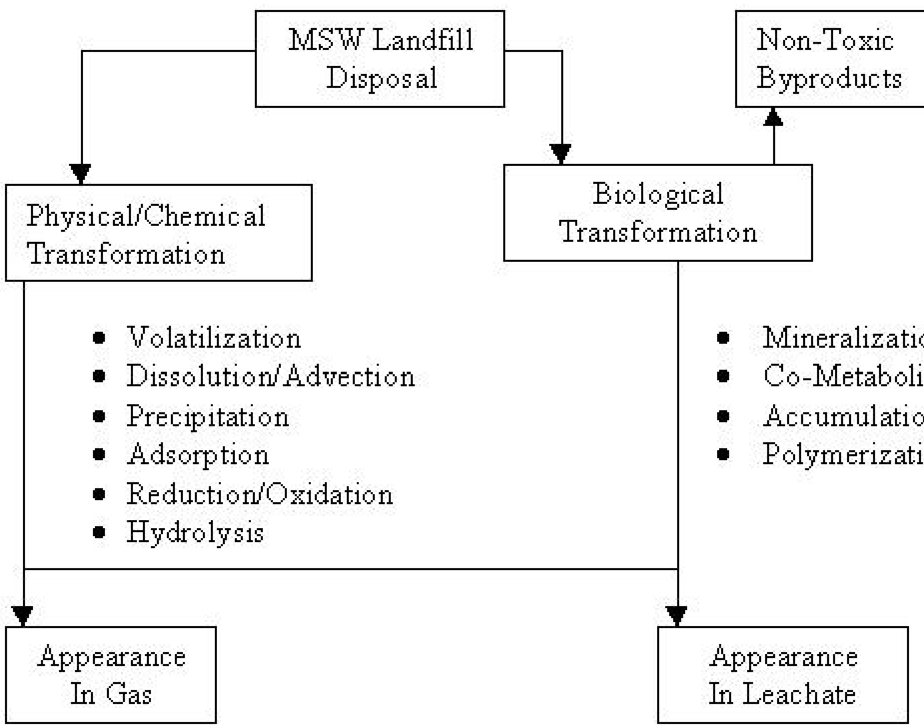


Figure 16 Fate and Transportation Mechanisms for Contaminants in MSW Landfills (Reinhart D.R. and Townsend T.G., 1998)

Mathematical Modeling

Many factors affect moisture routing through a landfill. The U.S. Geological Survey (USGS) has developed a mathematical model to consider the impact of these parameters on design and operations. The Saturated and Unsaturated Flow and TRAnsport (SUTRA) model was used to model the re-circulating landfill.

> SUTRA is a finite-element simulation model for saturated-unsaturated, fluid-density-dependent ground-water flow with energy transport or chemically-reactive single-species solute transport. SUTRA may be employed for areal and cross-sectional modeling of saturated ground-water flow systems, and for cross-sectional modeling of unsaturated zone flow. In addition, solute transport simulation with SUTRA may be used for modeling of variable density leachate movement (Souza W.R. and Voss C.I., 1997).

Leachate movement is predominantly characterized by unsaturated flow, except for perched leachate over impermeable layers and leachate mounding near the bottom of the landfill. Darcy's law, Equation 3, is used to describe unsaturated flow, just as it is used for saturated flow (Davis M.L. and Cornwell D.A., 1991; Tchobanoglous G. et al., 1992b).

Equation 3 Darcy's Law

$$Q = - KA \left(\frac{dh}{dl} \right)$$

where Q = leachate discharge, m^3/yr,

K = coefficient of permeability, m/yr,

A = cross-sectional area through which leachate flows, m^2,

dh/dl = hydraulic gradient, m/m,

h = head loss, m,

l = length of flow path, m

However, there are some important differences. Under unsaturated conditions pressure is less than atmospheric pressure, which explains why water will not flow into a borehole drilled into the unsaturated zone. The minus sign in Darcy's law arises from the fact that head loss always is negative, due to it being less than atmospheric pressure. The capillary forces that hold water against gravity cause this negative potential. Water will flow from a less negative to a more negative potential area, as long as the moisture content is above field capacity. The suction head at field capacity is 100cm by definition, therefore potential is extremely negative. As the moisture content increases, the suction head declines, until it reaches zero at saturation.

> The primary inputs to SUTRA are the physical characteristics of the solid matrix and fluid, porosity, permeability, dispersivity, and the unsaturated flow characteristics. Porosity is input on a node-wide basis while permeability and dispersivity are input by element. The SUTRA simulation is a mesh of nodes in cartesian coordinates which are then connected to quadrilateral elements. Output from the model provides degree of saturation (volume of water/volume of voids), fluid mass budgets, and depth of the head on the landfill liner as a function of the rate of leachate introduction and location or re-circulation device(s) (Souza W.R. and Voss C.I., 1997).

The power equations, Equation 4 (Reinhart D.R. and Townsend T.G., 1998), developed by Korfiatis assumed that due to the dominance of paper and fibrous material in the waste, the moisture retention characteristics of fine-grained materials could be used as a preliminary description for the moisture retention characteristics of solid waste. Figure 17 depicts the relationship between unsaturated hydraulic conductivity and moisture content.

Equation 4 Power Law equations

$$h = h_s \left(\frac{\theta}{\theta_s} \right)$$

Where: h = the suction head, m,

h_s = saturation suction head, m,

θ = volumetric moisture content, dimensionless,

θ_s = saturation volumetric moisture content, dimensionless,

b = suction head fitting parameter,

$$K = K_s \left(\frac{\theta}{\theta_s} \right)^B$$

Where: $K(\theta)$ = hydraulic conductivity at θ, m/yr

K_s = saturated hydraulic conductivity, m/yr

θ = volumetric moisture content, dimensionless,

θ_s = saturation volumetric moisture content, dimensionless,

B = permeability fitting parameter, dimensionless.

The Brooks and Corey equations, Equation 5 (Reinhart D.R. and Townsend T.G., 1998), were used to model the sand and gravel components of the model. The following example demonstrates the application of this model and how well these correlations are represented on small-scale.

Equation 5 Brooks and Corey equations

$$k_r = \left(\frac{h}{h_s} \right)^{-2.75}$$

$$\theta = \left(\frac{h}{h_s} \right)^{4}$$

Where: k_r = relative hydraulic conductivity, unitless

θ = volumetric moisture content, wet basis, m^3/m^3

h_s = saturation suction pressure, N/m^2,

h = suction pressure, N/m^2

Orange County Florida Landfill Field Testing

A 7.6m deep, 3,700m^2 test cell containing 4,800 Mg of municipal solid waste, with an estimated density of 1,000kg/m^3 was constructed with the specific goal of monitoring leachate flow characteristics (Reinhart D.R. and Townsend T.G., 1998).

Leachate was introduced to the cell by a 1.5hp centrifugal pump discharging to a 6m long by 60cm wide and 60cm deep gravel-filled trench. Flow control was provided permitting a range of leachate flow rates. Forty-eight cylinders were placed in horizontal lines at five levels within the cell. Electrical resistance of the cylinders was measured and related to moisture content. A total of $49m^3$ of leachate was pumped into the test cell over thirteen weeks. Leachate was introduced at rates of 0.38 to $0.5m^3$/day over a 1-hour period. Moisture block data were recorded on an hourly basis.

Moisture content iso-clines were developed for each set of weekly data. Figure 18 depicts a typical iso-cline plot. The plots indicated that the wetting front spread in a progressive fashion during periods of continuos moisture introduction. Horizontal movement of leachate may have been less likely to occur compared to a more conventional operation, due to the absence of daily cover in the test cell. The rate of leachate movement through the test cell was used to calculate hydraulic conductivity that ranged from $8.6x10^{-5}$ to $1.4x10^{-4}$ cm/sec for moisture contents of 40 to 70 percent, wet basis.

The U.S. EPA funded the development of the Hydrologic Evaluation of Landfill Performance (HELP) computer program. The advantage of this program over SUTRA, are the two-dimensional and design alternative capabilities.

HELP is a quasi-two-dimensional hydrologic model of water movement across, into, through and out of landfills. The program was developed to conduct water balance analyses of landfills, cover systems, and solid waste disposal and containment facilities. As such, the model facilitates rapid estimation of the amounts of runoff, evapotranspiration, drainage, leachate collection, and liner leakage that may be expected to result from the operation of a wide variety of landfill designs. The primary purpose of the model is to assist in the comparison of design alternatives (Schroeder P.R. et al., 1994c).

By inputting the current Denton landfill data associated with "dry-tomb" techniques and then adjusting the rainfall to that of a high rainfall climate to simulate increased leachate/moisture, that would be necessary for a bioreactor to successfully operate. The model will allow the user to determine the best bioreactor design needed. The HELP program assumes Darcian flow, Equation 3, for vertical drainage through homogeneous, temporally uniform soil and waste layers. It does not consider preferential flow through channels such as cracks, root holes or animal burrows. As such, the program will tend to overestimate the storage of water during the early part of the simulation and overestimate the time required for leachate to be generated. Vertical drainage is assumed to be driven by gravity alone and is limited only by the saturated hydraulic conductivity and available storage of lower segments. The vertical drainage rate out of a segment is assumed to equal the unsaturated hydraulic conductivity of the segment corresponding to its moisture content. This is assuming that the moisture content is greater than the field capacity or the soil suction of the segment is less than the suction of the segment directly below it. The unsaturated hydraulic conductivity is computed by Campbell (Schroeder P.R. et al., 1994c) hydraulic equation using Brooks-Corey, Equation 5, parameters. It is assumed that all materials conducting unsaturated vertical drainage have moisture retention characteristics that can be well represented by Brooks-Corey parameters and the Campbell equation. The pressure or soil suction gradient is ignored when applying the Campbell equation; therefore, the unsaturated drainage and velocity of the wetting front may be underestimated. This is more limiting for dry conditions in the lower portion of the landfill, as will probably be for the Denton landfill.

Percolation through soil liners is modeled by Darcy's law, Equation 3, assuming free drainage from the bottom of the liner. The liners are assumed to be saturated at all times, but leakage occurs only when the soil moisture of the layer above the liner is greater than the field capacity. Leakage through the geomembrane is modeled theoretical and empirical equations. In all cases, leakage is a function of hydraulic head. The lateral drainage model is based on the assumption that the lateral drainage rate and average saturated depth relationship that exists for steady-state drainage also holds for unsteady drainage. This assumption is reasonable for leachate collection, particularly for closed landfills where drainage conditions should be fairly steady. Where drainage conditions are more variable, such as in the cover drainage system, the lateral drainage rate is underestimated when the saturated depth is building and overestimated when the depth is falling. Overall, this assumption causes the maximum depth to be slightly overestimated and the maximum drainage rate to be slightly underestimated. The long-term effect on the magnitude of the water balance components should be small. As with leakage or percolation through liners, the average saturated depth is computed from the gravity water and moisture retention properties of the drain layer and other layers when the drain layer is saturated. The program assumes that horizontal and vertical saturated hydraulic conductivity to be of similar magnitude and that the horizontal value is specified for lateral drainage layer.

Leachate re-circulation is assumed to be uniformly distributed throughout the layer by a manifold or distribution system. Leachate collected on one day for re-circulation is distributed steadily throughout the following day. Earlier discussions demonstrated that there will be various heterogeneous conditions causing impervious areas/layers for leachate and gas movement through the landfill cell.

The model can simulate water routing through or storage in up to twenty layers of soil, waste, geosynthetics or other materials for a period of 1 to 100 years. The program performs water balance analysis for a minimum period of one year, beginning January 1 and ending December 31. The condition of the landfill, soil properties, thickness, geomembrane hole density, maximum level of vegetation, etc., are assumed to be constant throughout the simulation period. The program cannot simulate the actual filling operation of an active landfill. Active landfills are modeled a year at a time, adding a yearly lift of material and updating the initial moisture of each layer for each year of simulation. (Schroeder P.R. et al., 1994c)

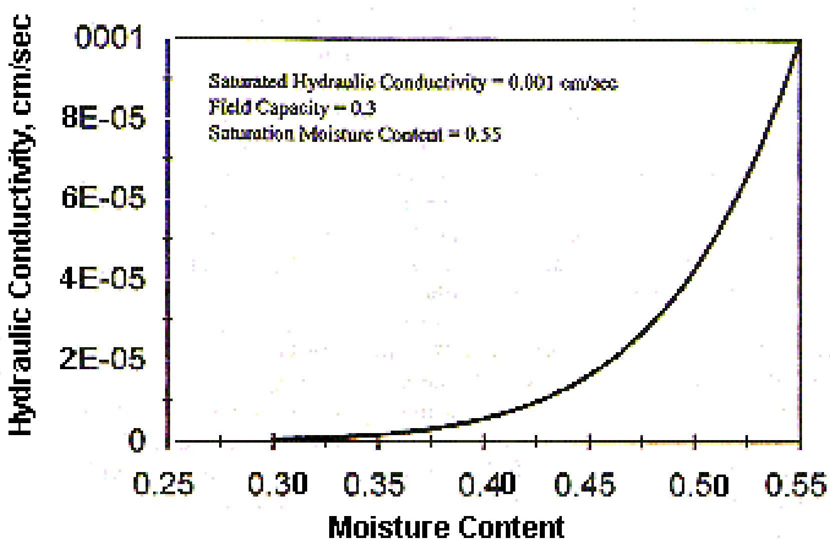


Figure 17 Unsaturated Hydraulic Conductivity and Moisture Content relationship (Reinhart D.R. and Townsend T.G., 1998)

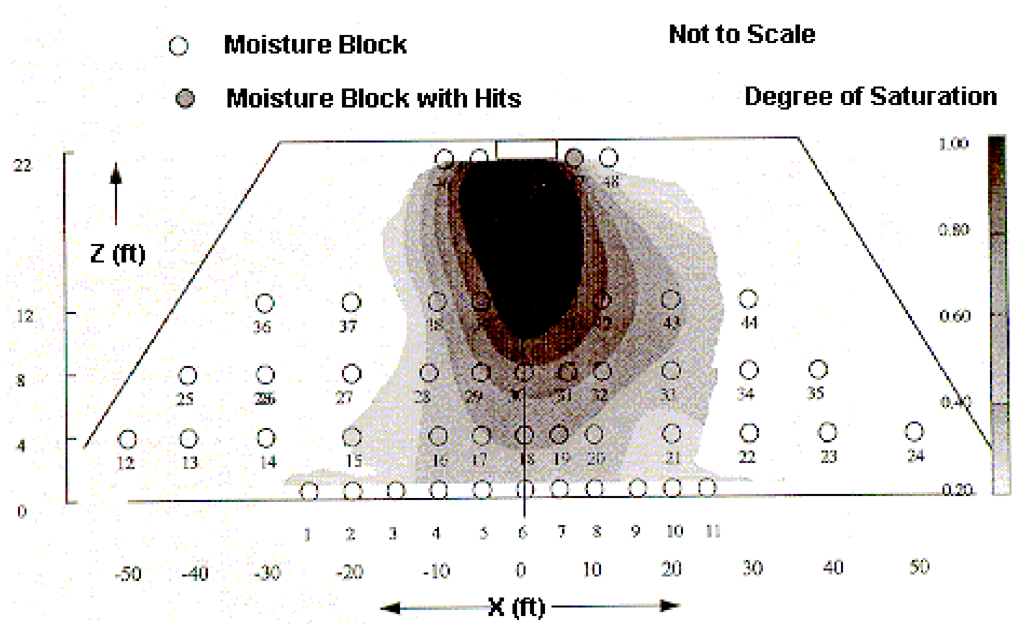


Figure 18 Leachate Movement Following Introduction using a Horizontal Trench -test cell, (Reinhart D.R. and Townsend T.G., 1998)

CHAPTER 5

LITERATURE SURVEY

Laboratory Scale

Many lab scale studies have been conducted to investigate the effects of leachate re-circulation on leachate quality, waste stabilization, waste settlement, gas production, attenuation of heavy metals, and other factors.

Moisture content, pH, temperature, availability of macro- and micro-nutrients and the presence of suitable micro-organisms are the main parameters controlling the process of landfill stabilization and are therefore typically manipulated in lab studies.

Georgia Institute of Technology Experiment (Reinhart D.R. and Townsend T., 1999)

Conducted during the mid-1970s and supported by the USA EPA. This experiment conclusively proved the effectiveness of leachate re-circulation on waste stabilization. Conclusions drawn:

- Leachate re-circulating columns produced low COD/TVA leachates in a shorter time period as opposed to a more gradual decline in the control cell.
- The peak COD and TVA concentrations in the leachate re-circulated columns were less than the control column.
- pH remained more neutral in the leachate re-circulated column than the control column.
- pH control and leachate re-circulation gave the best performance with rapid decline in COD and TVA concentrations.

- Inoculation with wastewater sludge did not accelerate the degradation process.

University of Louisville (Reinhart D.R. and Townsend T., 1999)

The lab scale study was performed to demonstrate the advantages of leachate re-circulation and the feasibility of providing leachate treatment. Additionally the effect of leachate pH and nutrient control on biological stabilization of shredded and unshredded waste was determined. Conclusions drawn:

- Leachate re-circulation with leachate control established anaerobic biological population in the fill rapidly.
- Nutrient control did not have any significant effect on stabilization of organic content of the refuse
- Shredding did not have any effect on biological stabilization of the refuse
- Leachate re-circulation with pH control lead to accelerated biological stabilization of the organic content of the refuse reducing the ultimate required time for site use (land reclamation)
- Leachate re-circulation with pH control lead to significant reductions in BOD, COD, and TOC
- Leachate re-circulation with pH control can be used as an effective leachate treatment process.

Pilot Scale

Table 6 lists ten pilot scale bioreactor experiments that have clearly demonstrated the advantages of operating a landfill cell as a bioreactor.

Location	**Dimension**	**Techniques Applied**	**Conclusion**
Georgia Institute of Technology	4 columns: 0.9m diameter, 3m waste depth	Re-circulation, pH control, sludge addition	▪ Re-circulation with pH control produced low organic strength leachate faster ▪ Sludge had no effect
Georgia Institute of Technology	4 columns: 0.9m diameter, 3m waste depth	Re-circulation, addition of priority pollutants	▪ Re-circulation increased gas volume and rate, decreased leachate organic strength ▪ Re-circulation promoted reduction of inorganic and organic pollutants
Georgia Institute of Technology	2 cells: 3m x 3m x 4.3m	Re-circulation, sealing of cell	▪ Sealed re-circulation more conducive to methanogenic conditions than open air cell
University of Louisville	4 columns: 0.9m diameter, 2.4m waste depth	Re-circulation, shredding, pH control, nutrient addition	▪ Re-circulation with pH control produced low organic strength leachate faster ▪ Shredding and nutrient addition had no effect
Newcastle University	4 lysimeters: 0.5m diameter	Re-circulation, shredding, saturation vs free draining, waste density	▪ Shredding increased degradation rate ▪ No benefit from saturation ▪ Lower density increased waste degradation
Bornhausen Landfill, Germany	4 columns: 1.5m diameter, 1.35m waste depth	Re-circulation, initial saturation, water input rate varied	▪ Emission of inorganic and organic pollutants reduced due to re-circulation ▪ No increase in gas production or quality

Bornhausen Landfill, Germany	3 cells: $50m^2$ x 4m 2 cells: 0.6ha x 2m	Re-circulation, thin layer compaction	▪ Re-circulation cut stabilization in half
Binghamton, NY	9 cells: 17m x 23m x 6.4m	Re-circulation, sludge addition	▪ Re-circulation and sludge addition improved gas and leachate quality
Delaware Solid Waste Authority	5 areas: 3.6 to 8.9ha	Re-circulation: spray, recharge wells, horizontal infiltrators	▪ Re-circulation accelerates waste biodegradation ▪ Re-circulation improved gas quality and leachate at low capital cost
Lycoming, PA	52.6ha max depth 21m	Re-circulation: spray, trenches, inspection wells	▪ Re-circulation increases waste degradation and methane generation ▪ Ponding and saturation lead to leachate outbreaks ▪ Injection wells most efficient

Table 6 Summary of Pilot Scale Bioreactor Investigations (Reinhart D.R. and Townsend T.G., 1998)

Full Scale

Table 7 provides a brief overview of fifteen recent landfills that have been granted permission to implement full-scale bioreactor tests in North America, U.K., Europe and Australia.

Location	**Size**	**Start Up Date**	**Leachate Re-circulation Technique**	**Leachate Re-circulation Cost**	**Comments**
Kootenai Co., Idaho	7 acres	1993 (open) 1995 (leach. Recirc)	Surface spray (summer only) trenches 80' spa Wells	$1,035,000 amortized + op = $449,600/yr	First lined landfill in Idaho
Bluestem SWA, Linn Co. Iowa	0.5 acres 8500 tons waste divided into 2 subcells	1998	Trenches 15'spa 2820 gals/d	$959,000 (cell construction)	Experimenting with bag opening, biosolids addition
Milwaukee	200' x 40'	1999	Trenches	NA	No compaction, shredded, biosolids added
Keele Valley LF Toronto, Canada	Pilot	1990	Vertical wells – 0.5 wells/acre ~50-100 gpm		Well water added to adjust MC not leachate
Eau Claire, WI 7 Mile Creek SL	800 tpd landfill, phase 1 at200		Trenches 25' spa 1.8 gpd/ft^2	NA	Tire chips acceptable in trenches, gas production increased by 25% in wells near recirculation
Yolo County, CA	2 10,000 ft^2 cells 9,000 lb MSW each 40' deep	1995	14 infiltration trenches at surface	$563,000 (cell con-struction)	Enhanced gas production, settlement, Shredded tires successful in LFG collection

Lower Spen Valley LF West Yorkshire, UK	2 cells ~ 950 tonnes waste ~ 9600 ft^2 ea ~ 18 ft deep	1991	Trenches	NA	Biosolids and wastewater addition Low temperture prevented max. gas production
Crow Wing MSW LF, Minn	12.8 acres	1997	11 trenches, 50' spacing, filled with shredded tires, 25 g/d/ft	$290,000, $72,500 savings/yr (1997-8)	No off site hauling of leachate in 1998, Recirculation operated 3 mos/yr
Worcester Co. LF, MD	17 acres, 80' deep	1990	Vertical wells surrounded by 25' of gravel blanket	$50,000 Net benefit $3.2 mill per 17-acre cell (after mining)	Avg. 65% of leachate recirculated Upper layers did not degrade extensively
North Central Georgia	78.5 ac	1996	Sprayed on the working face during day	$0.011/gal leachate	5 % increase in compaction achieved
Lyndhurst LF, Melbourne, Australia	1.3 ha	1995	Recharge wells and trenches	NA	Complete instrumentation for monitoring leachate, temperature, gas, climate, moisture distribution, head on liner
VAM Waste Treatment, Wijster, the Netherland	7062 m^2	1997	Trenches 10 m hor, 3 m vertical spacing (plus surface infil-tration at 5 m spacing)	NA	Gas collection in wood chips at the top liner. Filled with mechanically separated organic fractions <45 mm diameter
Baker Rd LF, Columbia County, Georgia	8 acres, 10 ft deep	1996	20 vertical wells.	$25 – 30,000 capital, O& M costs not reported	Air injected into LCS system, Settlement increased by 4.5%, biodegradation rate increased by >50%

Live Oak LF, Atlanta, Georgia, USA	2.5 acres, 30 ft deep	1997	27 vertical wells, 5-15 ft deep, 18 air injection wells		Air and liquid injection into same well improved fluid distribution
Trail Road LF, Ontario, Canada	270 m x 500m	1992	Infiltration lagoons	NA	Lagoons were moved around ~ 50% of field capacity achieved

Table 7 Recent Full-Scale Bioreactor Landfill Tests, (Reinhart D., 1999)

Other investigations that are also occurring deal with treating the leachate before discharging to publicly owned wastewater treatment works. The Huneault Landfill, located in the city of Gloucester, Ontario, receives construction/demolition waste and industrial/commercial/institutional waste. The landfill produces about 57,000 m3/yr of leachate.

A system consisting of a peat filter followed by an engineered wetland was selected to treat leachate before discharging it into the receiving environment. Laboratory batch adsorption and continuous column studies demonstrated that the peat filter is highly effective in leachate treatment. Removal rates of 85%, 99%, and 85% were achieved for iron, lead and zinc, respectively. As much as 30% removal was achieved for boron and 34-47% removal was observed for BOD_5.

The peat filter and engineered wetland treatment system was designed and constructed in 1994/1995 and came into operation in August of 1995. This system consists of four cells, the first one comprising of the peat filter and the other three cells serving as free surface water engineered wetlands.

Field monitoring of the peat filter and engineered wetland based on two sampling events showed removal efficiencies of 83%, 94%, 99%, 55% and 87% for boron, iron, lead, zinc, and BOD_5 respectively. These results confirm that this system is quite effective for the treatment of leachate (Castonguay N. et al., 2000).

Table 8 shows a comparison describing the noticeable leachate quality differences, which is attributed to a large extent to the type of waste being landfilled.

Denton landfill will have its own unique characteristics too. Treatment methods will therefore need to be specific to each landfill's leachate.

	HUNEAULT LANDFILL (1990 1995)			NEPEAN LANDFILLS			ONTARIO LANDFILLS		
	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg
Ammonia	0.1	26.51	15.82	<0.1	1302	318.79	0.03	1302	171.3
BOD5	1.6	81	26.56	270	66000	14176	1	66000	4975.6
Alkalinity	185	1696	1370.4	691	11640	5459	7	11640	2626
Nickel	0.02	0.17	0.05				0.01	0.3	0.07
Copper	0.0016	4.5	0.52	0	1.05	0.11	<0.001	8.8	0.11
Diss. Org. Carbon	17.5	114	82.6	29	14365	4064	1	14365	1630.9
Tot. Kjeldahl N	2.1	37.7	26.6	6.2	2488	561.2	0	2488	256.3
Boron	0.37	12	8.79	0.34	5.1	2.52	0.12	63.2	10.53
Iron	0.003	8.086	3.11	0.38	3853	395.91	0.03	3853	130.79
Conductivity	669	4540	3533	700	21500	9833	475	26100	6088
Diss. Inorg. Carbon	16	455	282.3				1	5800	497.3
TDS	1920	2572	2193				196	9030	4327
Potassium	11.8	80.4	63.63	5	899	275.6	0.1	2000	207
Magnesium	17	171	106.97	16.4	1972	438.6	4.8	7600	231.9
Sodium	53.9	476	332.94	28.4	8760	1473.2	6.1	8760	577.1
Manganese	0.13	8.56	1.97	0.01	14.1	2.73			
Organic N	1.27	37.6	12.54						
Phenols	0	1.12	0.03	6	6620	1760	0	6620	493.8
COD	69.2	2897	242.65	558	37209	16050	1	47300	7855.2
TSS	12	140	57.14	<10	3210	458	3	8130	445
Chlorides	45.5	1260	349.17	39	5448	1691.7	4	5448	744.9
Lead	0	0.28	0.03	0	0.58	0.04	0	0.8	0.05
Zinc	0.01	1.83	0.04				0	82.6	1.47

Notes: all concentrations are in mg/l

Table 8 Leachate Quality Comparison from Ontario Landfills, (Castonguay N. et al., 2000)

CHAPTER 6

BIOREACTOR DESIGN

Design

For the most part, state and federal regulations (primarily RCRA Subtitle D) dictate the design of the modern landfill. Required design components include the liner, leachate collection facilities, gas collection and management facilities, and final cap. These same components must be adapted during the operational period of the bioreactor landfill to manage leachate, including liquid introduction, and to handle enhanced gas generation. The following issues must be addressed to produce a successful project that satisfies regulatory concerns (Pacey J. et al., 1999; Pacey J. et al., 1999).

Cell Size

For economic and regulatory reasons, an emerging trend in traditional landfill design is to build deep cells (or phases) that are completed within two to five years. This trend bodes well for bioreactor landfill evolution. Phased cell construction can more easily take advantage of emerging technological developments, rather than committing long term to a design that might prove to be inefficient. Denton's Landfill Site Plans Appendix shows that phased cell construction is being utilized. Once closed, methanogenic conditions within the cell (phase) are optimized and gas generation and extraction are facilitated. However, extremely deep landfills might be so dense in the lower portions that refuse permeability will inhibit leachate flow. In these instances, it might be necessary to limit addition and/or re-circulation to the upper levels or develop adequate internal drainage management capability.

Maximum Allowable Leachate Head

Federal regulations prescribe a 0.305m (Wells J., 1999) maximum allowable leachate head on the bottom liner. This criterion can be readily achieved through appropriate design and bottom-liner slopes, drainage-layer flow distances, and hydraulic conductivity of the leachate drainage layer. The design can be aided by the use of mathematical models such as HELP3 developed by the Army Corps of Engineers (Schroeder P.R. et al., 1994a). Since leachate-head predictions are based on mathematical models, regulatory agencies may require monitoring to verify performance.

Liquid Management

An estimate of the design flow rates and liquid storage and supplementation capacity must be developed for the liquid management system. Sufficient storage will be required to ensure that peak leachate-generation events can be accommodated. Sufficient liquid supply (i.e., leachate, water, wastewater, or sludge) must be ensured to support project goals. The volume of liquid needed to reach waste field capacity can be based on prior field studies, model predictions, or landfill-specific measurement. Expressed as a volume per mass of solid waste, the range of liquid addition to reach field capacity is 104,306 - 208,612 liters per 1,000 tonnes (Wells J., 1999) of solid waste (Reinhardt J.J. and Ham R.K., 1974).

There are various methods of adding liquid. Methods that directly apply the leachate and water to the solid waste can target moisture supplementation levels during active landfilling. One option is to apply the liquid at the working face as refuse is placed into the landfill. In this case, however, operators must be prepared to deal with increasing gas generation shortly thereafter. Another option is to add moisture after waste placement, which controls the onset of rapid gas generation. Applying leachate and water to solid waste already in place can be accomplished by using surface irrigation systems, infiltration ponds, injection wells, or trenches. Selection considerations include climate, malodors, worker exposure, environmental impacts, evaporative loss, reliability, uniformity, and aesthetics. Buried trenches or vertical wells offer advantages of minimum exposure pathways, good all-weather performance, and favorable aesthetics. However, they may be adversely impacted by differential settlement. Guidance on liquid addition, alternative design, and performance can be found in Reinhart and Townsend (1997) (Reinhart D.R. and Townsend T.G., 1998).

Adding liquid to solid waste will increase its density, which can be of critical importance in the design of load-bearing structural members in the landfill. Most notably, the leachate and LFG collection system must be designed to accommodate the increased load, which may be as much as 30% heavier because of expected moisture uptake and settlement. The design process for determination of the buried leachate pipe load-bearing capacity is described in (Harrison S. and Watkins R.K., 1996).

Landfill Gas Control System.

A bioreactor landfill will generate more LFG in a much shorter time than a drier landfill will. To efficiently control gas and avoid odor problems, the bioreactor LFG extraction system may require installation of larger pipes, blowers, and related equipment early in its operational life. Horizontal trenches, vertical wells, near-surface collectors, or hybrid systems may be used for gas extraction. Greater gas flows are readily accommodated by increased pipe diameter as capacity increases as the square of pipe diameter.

Liquid addition systems should be separate from gas extraction systems to avoid flow impedance. The porous leachate removal system underlying the refuse should be considered for integration with the gas extraction system.

Enhanced gas production can negatively impact side slopes and cover if an efficient collection system is not installed during active landfill phases. Uplift pressure on geomembrane covers during installation can cause ballooning of the membrane and may lead to some local instability and soil loss. Temporary venting or aggressive extraction of gas during cover installation might facilitate cover placement. Once the final cover is in place, venting should be adequate to resist the uplift force created by LFG pressure buildup. The designer should consider the pressure buildup condition on slope stability when the collection system is shut down for any significant amount of time.

Landfill Stability

Addition of liquid into the refuse to increase biological activity will increase the total weight of the refuse mass and may cause an increase in internal pore pressure. This stability issue can be readily assessed and resolved with standard geotechnical analyses (Maier T.B., 1998). Seismic effects should also be considered during geotechnical analysis, when appropriate.

Settlement

A bioreactor landfill will experience more rapid, total, and complete settlement than will a drier landfill. Accelerated settlement results from both an increased rate of solid waste decomposition and increased compression through higher specific weights. Settlement during the landfilling operations will impact the performance of the final surface grade, surface drainage, roads, gas-collection piping system, and leachate-distribution piping system. Because of the significant increase in settlement magnitude and rate, it could be very beneficial to overfill the refuse above design grade before placement of the final cover. Alternatively, a significant benefit may accrue if final cover and final site-improvement installations are postponed and the rapid settlement is used to recapture airspace. Settlement impacts can be readily accommodated by the project design. Since settlement will be largely complete soon after landfill closure, long-term maintenance costs and the potential for fugitive emissions will be avoided.

Operations

The bioreactor landfill is a waste treatment system. During landfill operations, it requires closer attention to system performance than the drier landfill does. Successful operation of a bioreactor landfill depends on control and monitoring of biological, chemical, and hydrologic processes occurring within the landfill. Operational and maintenance programs addressing settlement, LFG, and leachate may be reduced to a minimal level once the landfill is closed and the refuse is largely stabilized.

Pretreatment or Segregation

Bioreactor operations are most efficient and effective where the refuse has high organic content and large exposed specific surface area. For this reason, bioreactor operations should be concentrated on waste segregated to maximize its organic content and shredded, flailed, or otherwise manipulated to increase its exposed surface area. Waste segregation could include separation of construction and demolition wastes from MSW. Limited shredding can be obtained by spreading refuse in thin lifts and using landfill equipment to break open plastic bags and break down containers. Mechanical shredding can be efficient and effective in reducing particle size and opening bags; however, it is an intensive, high-maintenance, and high-cost activity that might not be cost-effective. Moreover, shredded wastes may become exceedingly dense after placement, thereby limiting moisture penetration.

Leachate Seeps

Adding liquids to solid waste landfills increases the potential for leachate seeps or breakouts, and the landfill must be operated to minimize such possibilities. Leachate must be precluded from contaminating storm-water runoff. Monitoring for leachate seeps is mandatory, and the operations plan must include a rapid response action to correct leachate seeps as they develop. Such measures as installation of slope and toe drains, surface regarding, filling and sealing cracks as necessary to reduce surface-water infiltration, and reducing the liquid addition rate are some of the standard methods used to address this condition. Managing liquid addition rate, amount, and location can limit the potential for slope seeps.

Daily and Intermediate Cover

The use of soil cover in a bioreactor landfill requires special attention. A cover more permeable than the waste can direct leachate to the sides, where the leachate must be properly collected and drained. Low-permeability daily cover can create barriers to the effective percolation of leachate and water (Miller L.V. et al., 1991). It can also impede leachate distribution and LFG flow to collection and distribution systems; its ability to serve as a barrier should be reduced through scarifying, or partial removal, prior to placing solid waste over it. When placed within 15.24m of the slopes, it should be graded to drain back into the landfill to preclude leachate from reaching the slope and emerging as a seep. Use of alternative covers that do not create such barriers can mitigate these effects. In many cases, alternative covers have been found to be quite cost-effective when compared to soil.

Nutrients and Other Supplemental Additions

Nutrient requirements are generally supplied by waste components (Barlaz M.A. et al., 1990), but research suggests that nutrients and other biological and chemical supplements may enhance biological activity. Addition of such supplements has not yet been attempted in the field. As with waste segregation, or shredding, the costs of nutrients and other additions will need to be justified.

Optimum pH for methanogens is approximately 6.8-7.4. Buffering of leachate in order to maintain pH in this range has been found to improve gas production in laboratory studies. Particular attention to pH and buffering needs should be given during early stages of leachate re-circulation. Careful operation of the landfill bioreactor initially through slow introduction of liquids should minimize the need for buffering.

Bioreactor Management

It is important that operators of each bioreactor project develop a detailed and thorough management plan addressing project goals: design, operation, and maintenance; training; monitoring; contingency considerations; and QA/QC elements. All issues and solutions should be addressed in detail within these programs to the satisfaction of regulators and the public. The bioreactor landfill is possible now that Subtitle D mandates an environmentally secure environment. Within Subtitle D, some management flexibility is allowable to optimize the benefits available through controlled management of the organic decomposition process. Under certain conditions, the bioreactor landfill as seen in Figure 19, may be a viable technical option for landfill management.

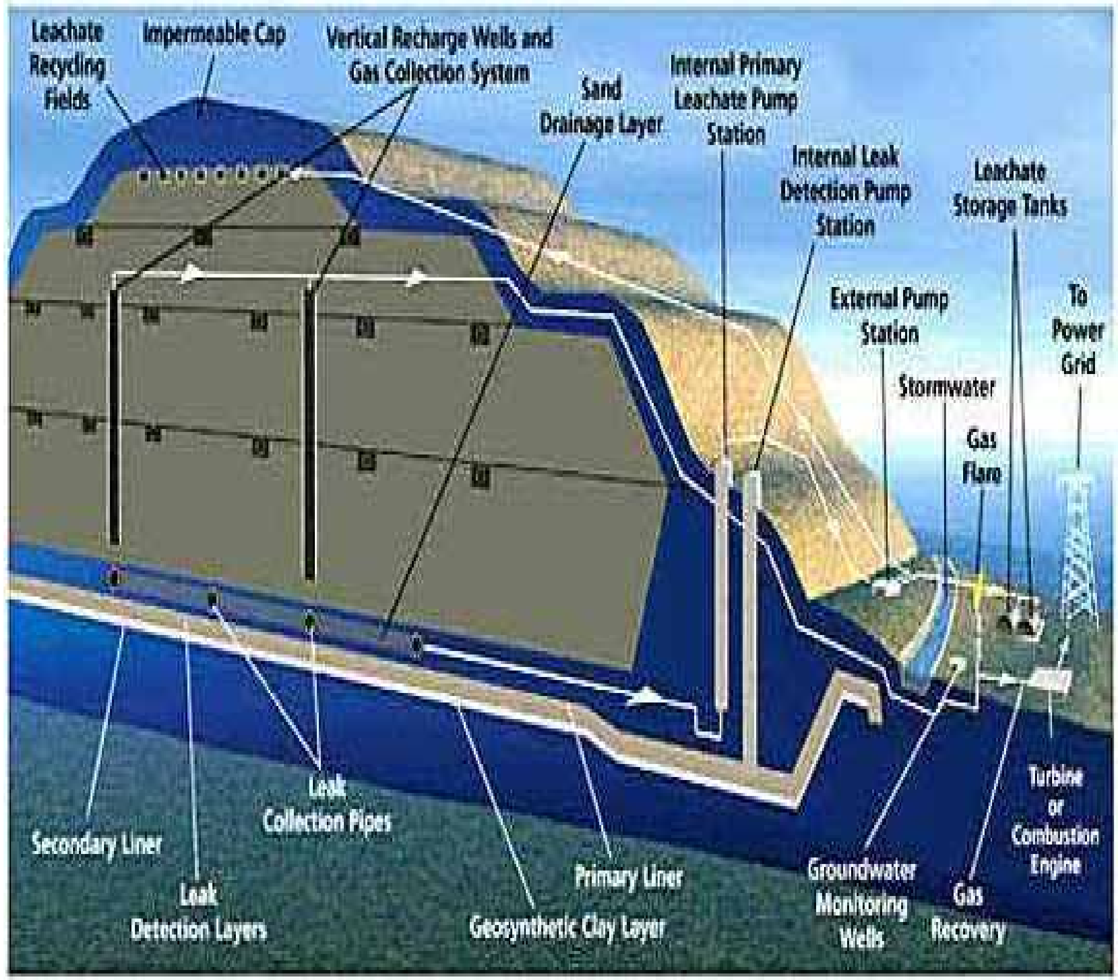


Figure 19 Bioreactor Design {Phaneuf , R.J. and Vana, J.M., 1999}

Hydrologic Evaluation of Landfill Performance Model

Chapter 4 defined how the HELP program functioned. The following data was input into the HELP model: (Schroeder P.R. et al., 1994a)

1. Units: Customary

2. Location:

    City Name and State: Denton, TX

    Latitude 33.12

3. Temperature data file names

    Denton Climatic Data Appendix shows some of the data

    Minimum Temperature: 1960-1990 daily minimums

    Maximum Temperature: 1960-1990 daily maximums

4. Evapotranspiration information:

    Evaporative Zone Depth: 12.0 in

    Max. Leaf Area Index: 3.5

    Growing Season Start Date: 63 (based on Dallas)

    Growing Season End Date: 329 (based on Dallas)

    Average Wind Speed: 9.5 mph

    Relative Humidity - First Quarter: 66% (based on Dallas)

    Relative Humidity - Second Quarter: 68% (based on Dallas)

    Relative Humidity - Third Quarter: 63% (based on Dallas)

    Relative Humidity - Fourth Quarter: 66% (based on Dallas)

5. Precipitation data:

Denton Climatic Data Appendix shows some of the data

Daily Precipitation: 1960-1990 daily recordings

7. Solar radiation data

Use simulation generated data based on climatic inputs

8. Soil and design data file name

Layer types: 4 - vertical percolation, lateral drainage, barrier soil liner, and geomembrane liner with associated layer thickness, soil texture no, total porosity, field capacity, wilting point, saturated hydraulic conductivity, max drainage length, drain slope, leachate/drainage re-circulation, re-circulate to layer #, subsurface inflow, geomembrane pin-hole density, geomembrane installation defects, geomembrane placement quality, geotextile transmissivity.

Program has default data to aid in the determination of input values. Used Denton Landfill Phase 2 landfill design to guide decision-making.

9. General landfill and site information

Assumed 9 acre cell with 100% possible runoff

Program was allowed to determine initial moisture content

10. Soil Conservation Service runoff curve number information

Program permitted to compute curve number

CHAPTER 7

RESULTS AND DISCUSSION

Hydrologic Evaluation of Landfill Performance

One of the objectives for this feasibility study was to utilize the Hydrologic Evaluation of Landfill Performance (HELP) model. The environmental engineering design program is used to assist landfill design engineers to consider the many factors specific to the conditions of the potential landfill. The Corp of Engineers released version does have a user-manual, but no live technical support. Without sufficient programming experience to debug all the errors, it was not possible to make the program run the full simulation, after loading all input data.

The DFW landfill is benefiting from the capture of methane, powering electric generators, which is providing electricity to homes in the Dallas-Ft.Worth metroplex. This landfill receives similar municipal waste to the Denton landfill, and is also located in a similar climate and soil region. However, if they had a bioreactor cell in operation, the methane generation and degradation rates would in all likelihood be far higher.

Areas of Refinement

Debugging the HELP software program to ensure that all data would be accepted to run the simulation, would aid in a more accurate feasibility assessment for a bioreactor.

The model does allow for up to 100 years of data to be entered. However, only 10 years of daily precipitation and temperature were entered due to programming malfunctions. The program was allowed to compute hourly solar radiation. An improvement to this could be through the collection of solar radiation data from another

WBAN station and then applying the necessary algorithms to more accurately reflect the conditions at Denton. The evaporative zone depth, maximum leaf area index, growing season and humidity were based on Dallas, TX default data supplied with the program. This could be refined to more closely depict the Denton Landfill conditions, if data could be collected on the premises.

Values and Preferences

> Statutes enacted during the 1960s and 1970s reflect public attention to the workplace and the environment; they resulted from political deliberation about what a decent, self-respecting society with a particular history would do about the work-place, the environment, civil rights, and public safety and health. These laws express a common perception of ourselves and the values we stand for as a moral community; they are not intended to satisfy personal preferences. When we make public law and public policy, we put both the devil and the policy analyst behind us, for we are to consider shared values and common intentions, not simply personal interests. Public issues must be discussed in public terms. What counts in public policy is a conception of right and wrong - a conception of the good society - not just what works for you (Sagoff M., 1988).

Sustainable Development

We can make educated guesses about where we are heading, by recognizing some of the major trends from the past and present. An old Chinese proverb states: if you do not change the direction in which you are headed, you will end up where you are headed.

Worldwatch Institute believes that by 2030 alternatives to the current dependence on fossil fuels will have taken place. Northern Europe and the United States will hopefully have become far more reliant on wind power and hydropower. Northern Africa and the Middle East would utilize direct sunlight as their main energy source. Japan, Indonesia, Iceland and the Philippines would be tapping their ample geothermal energy reserves (Seitz J.L., 1995).

The throwaway mentality that has been so prevalent in the United States is slowly being replaced by the recycling mentality. Many countries have developed a recycling program, but waste reduction in the packaging of goods still needs to be strongly encouraged. Alternative waste disposal methods such as the bioreactor technology, encourage the productive use of greenhouse gases, while accelerating the decomposition process.

CHAPTER 8

RECOMMENDATIONS FOR FUTURE RESEARCH

> Science contributes moral as well as material blessings to the world. Its great moral contribution is objectivity, or the scientific point of view. Professors serve science and science serves progress. It serves progress so well that many of the more intricate instruments are stepped upon and broken in the rush to spread progress to all backward lands (Leopold A., 1966).

Nontechnical Barriers to the Bioreactor Landfill

Research and limited field-scale experience offer solid technical evidence of the value of the bioreactor landfill. The challenges of non-technical barriers still face the bioreactor landfill. Principal among these is:

- Limited regulatory awareness and negative perception;
- Absence of site-specific performance quantification;
- Limited availability of project economic assessments;
- Insufficient project-sustainability experience;
- Lack of financing experience;
- Extended time expectations for planning, permitting, and licensing; and
- Increased regulatory constraints and conditions.

These non-technical issues and uncertainties must be researched further to fully evaluate the viability of potential projects and gain acceptance for the concept (Pacey J. et al., 1999).

Denton Landfill Impact Assessment

An impact assessment was performed when originally siting the landfill for Denton. Creating a new baseline of data before moving toward bioreactor technology, would verify any significant changes especially with regards air quality, surface water, soil and ground water, visual impacts, and socio-economics resulting from this change in processing and handling of the waste stream (Canter L.W., 1996).

Limit Environmental Impacts

Rapid stabilization offers a major long-term environmental benefit in terms of reducing risk: Waste and leachate will have been exposed to all potential detrimental environmental impacts during the operational life of the landfill, rather than during a long post-closure period. Post-closure liquid flowing through the waste should not increase gas generation nor result in further release of organic or metal constituents into the leachate. Most external environments should be able to naturally manage long-term waste-related emission or leakage from a well-managed bioreactor landfill.

Waste stabilization is a relatively gray term in literature. Life cycle consideration for the bioreactor landfill is for 20, 100, or 500 years. For the purpose of the bioreactor landfill, food, green-waste, and paper products can be biodegraded to a stabilized status within a few years of landfill closure. The level to which these items are degraded in the bioreactor landfill extends well beyond what would otherwise occur in the conventional Subtitle D landfill, even in the event of total failure of its environmental containment system. Other organic constituents, such as wood, rubber, plastic, leather, and textiles, are slowly degradable and should not pose much of a long-term environmental threat from either a greenhouse gas or groundwater standpoint (Pacey J., 2001).

Economics

The bioreactor landfill offers several well-known and proven processes to achieve rapid degradation, and thus stabilization, of the relatively rapidly degradable organic waste materials within a relatively short term. Although it requires increased management

and more environmental controls, the bioreactor landfill can result in enhanced performance, fewer long-term environmental risks, and higher potential revenue to help defray operational costs. Over the long term this should result in considerable environmental and cost savings.

The operational issues for the bioreactor landfill are the same as have been permitted in the past.

Recognition of the potential environmental and economic benefits of the bioreactor has brought a new focus on the use of anaerobic and aerobic bioreactor processes. With the advent of Subtitle D landfills, there are now real possibilities to rapidly stabilize our waste so as to minimize post-closure environmental risk and gain near-term environmental and economic benefit. The bioreactor process is not complicated. Although the degree of management and monitoring is more sophisticated and challenging than with the conventional landfill, the benefits can be outstanding (Pacey J., 2001).

Summary and Conclusion

It is now time to seriously consider acceptance and adoption of the bioreactor landfill as a key strategy for deriving short- and long-term environmental, regulatory, monetary, and societal benefits. The bioreactor option is a direct result of engineering and building a new generation of environmentally sound landfills. It provides environmental security while permitting and encouraging rapid stabilization of readily and moderately decomposable organic waste components. It is hoped that the emerging bioreactor-landfill technology will point our solid waste industry toward taking a new look at a very effective option to managing our waste disposal.

> In human affairs, the logical future, determined by past and present conditions, is less important than the willed future, which is largely brought about by deliberate choices - made by the human free will. Rene Dubos (Seitz J.L., 1995).

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